

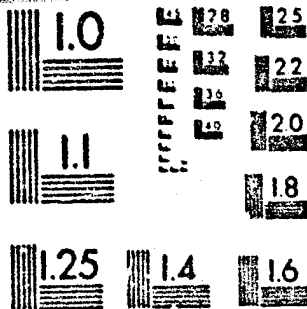
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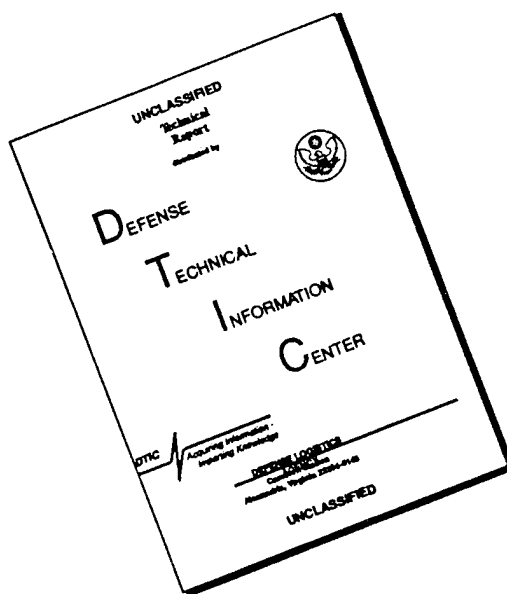
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Report 2418-F

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NASA

Composite Material Application To
Liquid Rocket Engines

(NASA-CR-170697) COMPOSITE MATERIAL
APPLICATION TO LIQUID ROCKET ENGINES Final
Report (Aerojet Liquid Rocket Co.) 314 p
HC A14/HP A01 CSCL 11D

N83-15360

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Final Report

by

D. C. Judd
Aerojet Liquid Rocket Company

Prepared For

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

Contract NAS 8-34623

RECEIVED 12/10/82

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1. Report No. 2418-F		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Composite Material Application to Liquid Rocket Engines				5. Report Date December 1982	
				6. Performing Organization Code	
7. Author(s) D. C. Judd				8. Performing Organization Report No.	
9. Performing Organization Name and Address Aerojet Liquid Rocket Company P.O. Box 13222 Sacramento, CA 95813				10. Work Unit No.	
				11. Contract or Grant No. NAS 8-34623	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration George C. Marshall Space Flight Center Huntsville, Alabama 35812				13. Type of Report and Period Covered Contractor Report, Final	
				14. Sponsoring Agency Code	
15. Supplementary Notes Project Manager - Dennis Gosdin NASA-Marshall Space Flight Center Huntsville, Alabama 35812					
16. Abstract The major objectives of this study were to (1) determine the extent to which composite materials can be beneficially used in liquid rocket engines, (2) identify additional technology requirements, and (3) determine those areas which have the greatest potential for return. The assessment was based primarily on weight savings but also considered material and fabrication costs, performance, life, and maintainability factors. Two baseline designs, representative of earth-to-orbit and orbit-to-orbit engine systems, were selected for analysis. All components of these baseline designs were evaluated to determine which could benefit most from fabrication with composites. Weight savings from 50 to 80% were predicted for selected components with the substitution of reinforced plastic composite (RPC) materials for metal, and overall engine weight savings from 25 to 30% were found possible. Various technology needs were identified before RPC material could be used in rocket engine applications, and follow-on activities addressing these needs were proposed. Metallic or ceramic composites offered advantages in high-temperature or performance-driven applications but otherwise were not competitive to RPC on the basis of weight or cost.					
17. Key Words (Suggested by Author(s)) Composite Materials, Weight Reduction Assessment, Lightweight Design, Barrier Coatings, Polymer Matrix Composites, Metal Matrix Composites, Liquid Rocket Engine Components				18. Distribution Statement Unclassified - Unlimited	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 280	
				22. Price*	

FOREWORD

The work described herein was performed at the Aerojet Liquid Rocket Company under NASA Contract NAS 8-34623, with Mr. Dennis Gosdin, NASA-Marshall Spaceflight Center, as project manager. The ALRC program manager was Mr. Roy Michel, and the project engineer was Mr. Craig Judd. ALRC material engineering specialists for the study were Mr. George Janser and Mr. Ed Carter.

The technical period of performance for the study was from 24 February 1982 to 30 November 1982.

The following individuals contributed significantly to this report:

Fred Fischietto (Structural Analysis)
Ralph Shultz (Drafting)
Craig Judd (Project Engineering)
George Janser (Materials Analysis)
Ed Carter (Materials Analysis)
Chuck O'Brien (Engine Systems)

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TABLE OF CONTENTS

	<u>Page</u>
I. Summary	1
A. Study Objectives and Scope	1
B. Results and Conclusions	3
II. Introduction	12
A. Background	12
B. Purpose and Scope	13
C. Approach	13
D. Program Schedule and Major Mileposts	15
III. Task I - Baseline Engine Configurations	17
A. Objectives	17
B. Engine Selections	17
C. Component Requirements Data Sheets	42
IV. Task II - Component Assessment and Identification	48
A. Objectives	48
B. Composite Properties and Fabrication Processes	48
C. Methodology and Evaluation Form	54
D. Component Selection	54
V. Task III - Conceptual Design Assessment	65
A. Objectives	65
B. Stress Analysis	65
C. Final Drawings and Weight Estimates	65
D. Outside Vendor Design Input Concerning Reinforced Plastic Composites	78
E. Outside Vendor Design Input Concerning Metal Matrix Composites	81
VI. Task IV - Criticality Ranking of Technology Needs	84
A. Objectives	84
B. Technology Needs	84
C. Criticality Ranking of Technology Needs	92

TABLE OF CONTENTS (cont.)

	<u>Page</u>
VII. Task V - Recommended Tasks	93
A. Objective	93
B. Recommendations	93
C. Program Plans for the Selected Components	94
VIII. Conclusions and Recommendations	119
A. Conclusions	119
B. Recommendations	120
References	121
Appendices	
A. Component Requirement Forms	A-1
B. Reinforced Plastic Composite Properties	B-1
C. Metal Matrix Composite Properties	C-1
D. Task II Evaluation Forms	D-1
E. Vendor Trip Memos	E-1
F. Technology Needs Definition Forms	F-1

LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
I	Technology Needs Cross-Reference Chart	5
II	Advanced Expander Cycle Engine Weight Data	29
III	LOX/LCH ₄ Cycle C Engine Weight Data	43
IV	Task II Evaluation Form	55
V	Task II Selected Components	63
VI	Component Metallic Weight Versus Composite Weight	79
VII	Outside Vendors Consulted	80
VIII	Plastic Matrix Versus Metal Matrix Comparison Chart	83
IX	Technology Needs Listing	85
X	Design and Analysis Steps for Recommended Parts	94

LIST OF FIGURES

<u>Figure No.</u>		<u>Page</u>
1	Overall Study Program Summary	2
2	JTV Valve Housing	7
3	LCH ₄ TPA Impeller Housing	8
4	OTV Nozzle Extension Shaft	9
5	OTV Skirt Support Ring	11
6	Major Milestone Schedule	16
7	OTV Engine Layout	18
8	Igniter/Injector Assembly (ALRC Drawing No. 1191990)	21
9	Chamber and Tube Bundle Nozzle (ALRC Drawing No. 1191991)	22
10	LO ₂ Boost Pump (ALRC Drawing No. 1191994)	23
11	LO ₂ Boost Pump (ALRC Drawing No. 1191996)	24
12	LH ₂ TPA (ALRC Drawing No. 1191997)	25
13	LO ₂ TPA (ALRC Drawing No. 1191999)	26
14	Shutoff Valve (ALRC Drawing No. 1193176)	27
14A	OTV Flow Schematic	28
15	LOX/LCH ₄ Engine Layout	33
16	High-Speed LCH ₄ TPA	35
17	High-Speed LOX TPA	36
18	Baseline Mode 1 Dual-Fuel and Alternate Mode 1 Low-Speed RP-1 TPA	37
19	Baseline Mode 1 Dual-Fuel and Alternate Mode 1 Low-Speed LOX TPA	38
20	Alternate Mode 1 Gas Generator Cycle Engine Thrust Chamber Injector	39
21	Alternate Mode 1 Coaxial Gas Generator	40
21A	LOX/LCH ₄ Engine Flow Schematic	41
22	Sample "Component Requirements" Form	47
23	Task II Schematic	49
24	Fabrication Processes	50
25	Reinforcement Characteristics	51

LIST OF FIGURES (cont.)

<u>Figure No.</u>		<u>Page</u>
26	Matrix Characteristics	52
27	Properties of Various Composites	53
28	Detailed Description of Task II Evaluation Form	57
29	LCH ₄ High-Speed TPA (ALRC Drawing No. 1196001)	66
30	High-Speed LOX TPA (ALRC Drawing No. 1196002)	67
31	LOX Low-Speed TPA (ALRC Drawing No. 1196003)	68
32	Support Structure - Throat, Combustion Chamber (ALRC Drawing No. 1196004)	69
33	Seat - Gimbal Bearing (ALRC Drawing No. 1196005)	70
34	Shaft - Nozzle Extension (ALRC Drawing No. 1196006)	71
35	Injector Housing (ALRC Drawing No. 1196007)	72
36	Support Ring - Skirt Extension (ALRC Drawing No. 1196008)	73
37	Jacket - Tube Bundle, Nozzle (ALRC Drawing No. 1196009)	74
38	Manifold - Coolant, Thrust Chamber (ALRC Drawing No. 1196010)	75
39	Housing - Valve, Propellant (ALRC Drawing No. 1196011)	76
40	Gear - Actuator, Valve (ALRC Drawing No. 1196012)	77
41	Technology Risk Assessment Procedure	86
42	Technology Need Definition, Barrier Coating Process	88
43	OTV Valve Housing	100
44	OTV Valve Housing Fabrication Process Flowchart	101
45	1196011 Valve Housing Technology Program and Component Testing	102
46	Schedule and Budget for the OTV Valve Housing	103
47	LCH ₄ Impeller Housing	105
48	LCH ₄ TPA Impeller Housing Fabrication Process Flowchart	106
49	1196001 LCH ₄ TPA Discharge Housing Technology Program and Component Testing	107
50	Schedule and Budget for the LCH ₄ TPA Impeller Housing	109
51	OTV Nozzle Extension Shaft Fabrication Process Flowchart	110
52	1196006 Shaft, Nozzle Extension Technology Program and Component Testing	111

LIST OF FIGURES (cont.)

<u>Figure No.</u>		<u>Page</u>
53	Schedule and Budget for the OTV Nozzle Extension	112
54	OTV Skirt Support Ring Fabrication Process Flowchart	114
55	1196008 Skirt Extension Support Ring Technology Program and Component Testing	115
56	Schedule and Budget for the OTV Skirt Support Ring	116
57	Schedule and Budget for Combining the Support Ring and Extension Shaft	118

I. SUMMARY

A. STUDY OBJECTIVES AND SCOPE

The major objectives of this study were to (1) determine the extent to which composite materials can be beneficially used in liquid rocket engines, (2) identify additional technology requirements, and (3) determine those areas which have the greatest potential for return. The assessment is based primarily on weight savings, but also considers materials and fabrication costs, performance, life, and maintainability factors as applicable.

The five-task study program summarized in Figure 1 was conducted to accomplish the stated objectives. Two engine systems were selected to be baseline configurations for both orbit-to-orbit and earth-to-orbit engines. All components from these baseline engines were assessed to identify those which could potentially benefit most from fabrication with composites.

Twelve components were ultimately selected for further study as a result of this assessment. Preliminary drawings of the twelve selected components were reviewed by structural analysts to establish wall thickness requirements and to validate the design integrity. Subsequent to the structural analysis, final cross-sectional drawings were prepared for the selected components, and accurate weights were determined by measuring the cross sections and determining the volumes.

Thought was then given to defining the technological barriers that would need to be overcome in order to successfully build production rocket components out of composite materials. A list of these technology needs was formulated, and a "Technology Needs Definition" form was filled out for each of the individual technology needs. This form was used to define each technology need, assess its risk, suggest an approach to the problem, and propose a solution.

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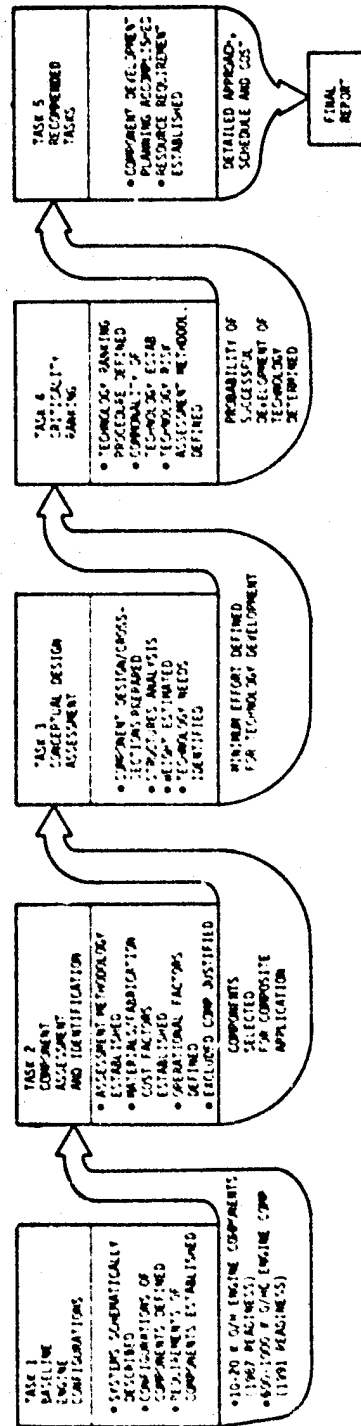


Figure 1. Overall Study Program Summary

I. A. Study Objectives and Scope (cont.)

Using the previously generated weight data and the information from the "Technology Needs Definition" forms, a "Technology Needs Cross-Reference Chart" was formulated. This chart displayed the number of components common to each technology and showed the percentage of weight reduction associated with the application of each technology need. This allowed the ranking of technology needs as well as specific components in terms of weight reduction payoffs. It also displayed an assessment of the risk associated with overcoming each technology barrier.

The "Technology Needs Cross-Reference Chart" was used in selecting four follow-on tasks recommended for further study and fabrication. The selected components not only showed promising weight savings through composite substitution, but their construction also encompassed the solution of a wide variety of technology needs.

Finally, a plan, schedule, and budget were formulated for the design, fabrication, and testing of the four selected components.

B. RESULTS AND CONCLUSIONS

This study determined that weight savings between 50 to 80% are possible on selected components when substituting reinforced plastic composite (RPC) materials for metal. This translates to an engine weight savings of 31.4% for the OTV engine and 25.5% for the LCH₄ 600K engine when composites are used wherever possible. The lower weight savings percentage for the LCH₄ 600K engine results from its greater number of hot-gas components (>350°F) which cannot use RPC substitution. Metal or ceramic matrix composites (MMC or CMC) could be used if high temperatures or performance became bigger "drivers" than weight savings. For the purposes of this study, however, RPC's were selected over MMC's and CMC's because of their lower cost, greater ease of fabricability, and higher specific strength.

I, B, Results and Conclusions (cont.)

It was also determined that a wide variety of technology needs (thirteen major categories) remain to be explored in substituting RPC's for metallic parts. Many of these technology needs lend themselves to easy solutions and were only included out of a desire for thoroughness (i.e., solar radiation effects, bearing surface lubricant, etc.). It is believed that the remainder of the more difficult technology needs can be solved through straightforward laboratory and fabrication test programs, as discussed in Section VI, B of this report.

Table I is an abridgement of the results obtained in Tasks I through IV and was used to select the follow-on tasks recommended for fabrication in Task V. The vertical columns show which technology needs are applicable to a given component and also give the percentage of engine weight savings possible if the component used composite substitution. The horizontal rows show the number of components common to each technology need, as well as the potential for weight reduction associated with the application of each technology need. Consequently, Table I allows the ranking of technology needs as well as specific components in terms of weight savings. It also displays our assessment of the risk associated with overcoming each technology barrier. A rating of "high risk" in no way signifies "next to impossible" in this chart; it merely indicates that the technology has only been proposed or theorized and that a reasonable amount of technology testing remains to be done to completely solve anticipated problems. A rating of "medium risk" indicates that less research and testing will be required to implement a given technology. A "low risk" technology need is one that is just short of being operational.

The recommended follow-on tasks were selected, using Table I as a guide. This ensured that a combination of promising weight savings and technology advancement features were incorporated into a minimum-cost, low-risk program. The components selected for fabrication in a follow-on program are as follows:

TABLE I
TECHNOLOGY NEEDS CROSS-REFERENCE CHART

- **ALLOWS RANKING OF TECHNOLOGY NEEDS AS WELL AS SPECIFIC COMPONENTS IN TERMS OF WEIGHT SAVINGS**
- **ALSO DISPLAYS ASSESSMENT OF RISK**

[illegible]

3

3 - Only Proposed or Permitted. Technology Testing Necessary to Solve Anticipated Problems

III - Long Research and Testing Necessary

1 - Joint Chiefs of Staff Operations:

I. B. Results and Conclusions (cont.)

<u>PN</u>	<u>Component</u>	<u>% Weight Savings Rank</u>	<u>Number of Technology Needs Addressed</u>
1196011	OTV Valve Housing	8	14
1196001	LCH ₄ High-Speed TPA Impeller Housing	4	17
1196006	OTV Nozzle Extension Shafts	1	6
1196008	OTV Skirt Support Ring	5	4

The graphite-epoxy OTV valve housing shown in Figure 2 was selected both for its significant engine weight savings (1.3%) and because of the fact that its fabrication would address a total of fourteen technology needs. It is also a component which could be immediately useful on several engines. This program could be completed in thirteen months for a cost of \$380K. It should be noted that this program could just as easily be split into distinct segments (i.e., technology, design, fabrication, and test) and performed over a 2- or 3-year time period with incremental funding (approximately \$150K/year).

The graphite-epoxy impeller housing shown in Figure 3 is the biggest engine weight saver on the 600K booster (2.5% engine weight savings) and is also the most complicated in terms of advancing the state of the art. Its complex shape and propellant exposure would result in the need to address seventeen technology needs before a housing could be successfully fabricated and tested. Its successful fabrication, however, would greatly facilitate the construction of any of the other engine subcomponents. This program is the most ambitious of the recommended tasks and could be completed in sixteen months for a cost of \$448K.

The graphite/fiberglass epoxy OTV nozzle extension shaft shown in Figure 4 shows the greatest percentage of engine weight savings of any of the components selected in this study (3.3%) and is also fairly simple to

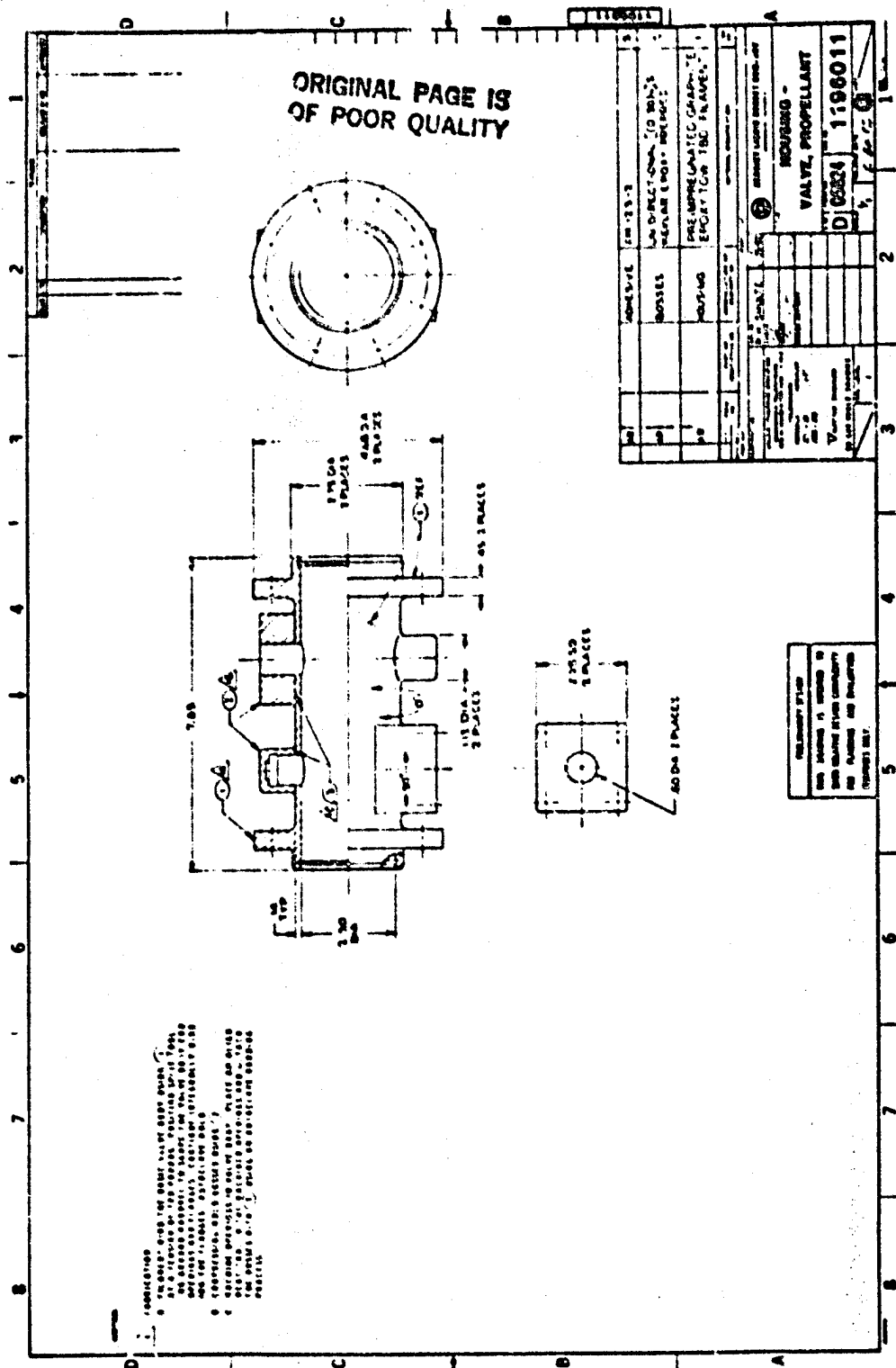


Figure 2. OTV Valve Housing

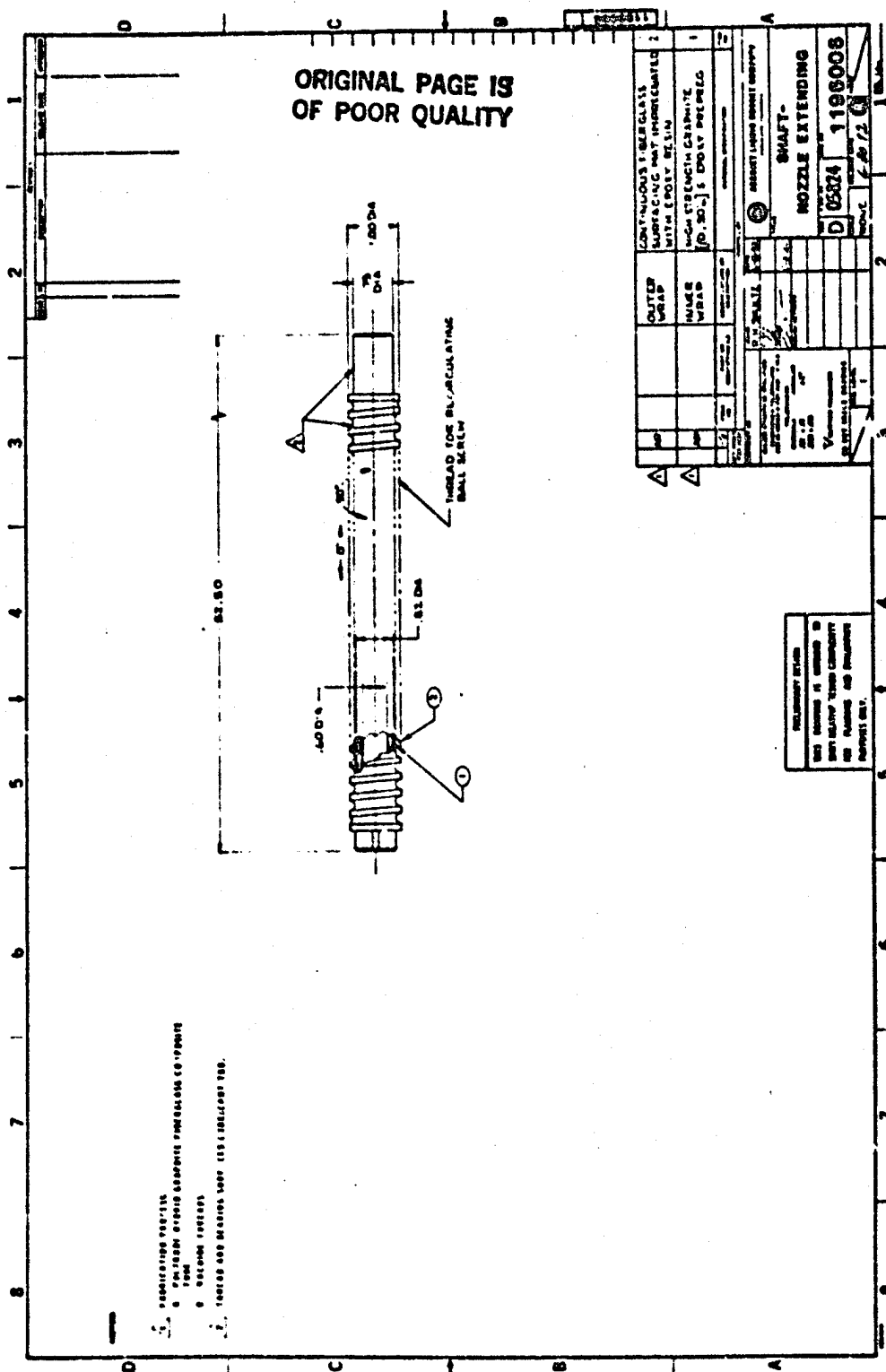


Figure 4. CTV Nozzle Extension Shaft

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I. B. Results and Conclusions (cont.)

fabricate. This program could be completed in thirteen months for a cost of \$231K. This is one of the simplest and least costly programs which could be performed and still result in significant weight savings.

The honeycomb/graphite-epoxy OTV skirt support ring shown in Figure 5 shows an engine weight savings of 2.2% and is also simple to fabricate. Additionally, it could be mated with the aforementioned extension shaft to form a subassembly. The support ring could be developed and tested in thirteen months for a cost of \$231K. Developing both the extension shaft and support ring together would result in certain economies because of the commonality in the technology testing and subcomponent tests. They could both be developed in the same 13-month time frame for a cost of \$281K.

It is recommended that a follow-on program be funded to 1) resolve technology needs, 2) design and fabricate a RPC subcomponent, and 3) test and evaluate the subcomponent. At the very least, a fabrication and materials technology program should be initiated to find solutions for the identified technology needs.

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II. INTRODUCTION

A. BACKGROUND

Many improvements in liquid rocket propulsion are being evaluated in an effort to define an economical space transportation system. One such improvement involves the use of composite materials in rocket engine design.

Composites are a family of high-performance materials consisting of a matrix reinforced with a fiber. The matrix is usually a thermosetting resin such as epoxy, a ceramic, or a metal such as aluminum. The reinforcement can be Kevlar, fiberglass, graphite, or boron in the form of either continuous fibers, chopped fibers, or whiskers. The combination of a matrix and a fiber results in a new composite material which is lighter, stiffer, and stronger than either of its constituents.

Recent studies indicate that weight reductions of 30 to 45% can be achieved for specific components of existing engines by using current and near-term composite technology. The Advanced Oxygen-Hydrocarbon Rocket Engine Study (NAS 8-33452), conducted by ALRC for NASA-MSFC, suggested that weight savings of 30 to 40% are possible for an entire LOX/hydrocarbon booster engine employing near-term and future composite technology.

Previous applications of composites in military, NASA, and commercial projects provide a broad base of experience. Rocket engine application, however, will impose additional material, design, and fabrication requirements due to such factors as hot gas and cryogenic temperature extremes, maintainability requirements, and a dynamic environment. Further, past experience has shown that the application of composites requires much hands-on development of design procedures and fabrication techniques which are unique to specific components.

II, Introduction (cont.)

B. PURPOSE AND SCOPE

The major objectives of this program were to 1) determine the extent to which composite materials can beneficially be used in liquid rocket engines, 2) identify additional technology requirements, and 3) determine those areas which have the greatest potential for return.

The scope included examining all major components from both earth-to-orbit and orbit-to-orbit engines to determine which could benefit most from composite substitution. The study guidelines dictated that the major consideration be weight savings, although cost, life performance, and maintainability were also considered. Drawings were made, technology needs were assessed, and a program plan was presented for designing, fabricating and testing four selected components.

C. APPROACH

To accomplish the program objectives, an effort involving five technical tasks was conducted. The tasks conducted were as follows:

1. Task I - Baseline Engine Configurations

Establish baseline representative engine configurations for both orbit-to-orbit and earth-to-orbit engines. This task was limited to schematic descriptions of the two selected engine systems and to documenting the general configurations and requirements of the engine components.

II, C. Approach (cont.)

2. Task II - Component Assessment and Identification

Establish a methodology for assessment of the component concepts. Apply this methodology to all baseline components from Task I and identify the components which can potentially benefit from fabrication with composites. A brief justification was also provided for each component where composite materials do not show a benefit.

3. Task III - Conceptual Design Assessment

Prepare conceptual design drawings (cross sections) of each component with potential composite application. Perform appropriate structural analyses as required to obtain realistic weight estimates. Define the minimum effort needed to illustrate the feasibility of technology development for each component.

4. Task IV - Criticality Ranking of Technology Needs

Establish a criticality ranking of identified technology needs. The degree of risk for successfully developing the technology was categorized between low (for components that are just short of being operational) to high (for components that have only been proposed or theorized). The degree of risk assessment included such factors as commonality, cost, schedule, and performance. Life-cycle cost data, where available or readily approximated, were also utilized.

5. Recommended Tasks

Recommend a minimum of two follow-on tasks involving component fabrication and testing. The recommendations encompass the integration

II. C. Approach (cont.)

of multiple technology needs and include a detailed approach, schedule, and estimate of the resources required.

D. PROGRAM SCHEDULE AND MAJOR MILEPOSTS

Figure 6 presents a detailed program schedule of the events in Tasks I through V. The mileposts shown include submittal of data for NASA approval, reviews, and task completions.

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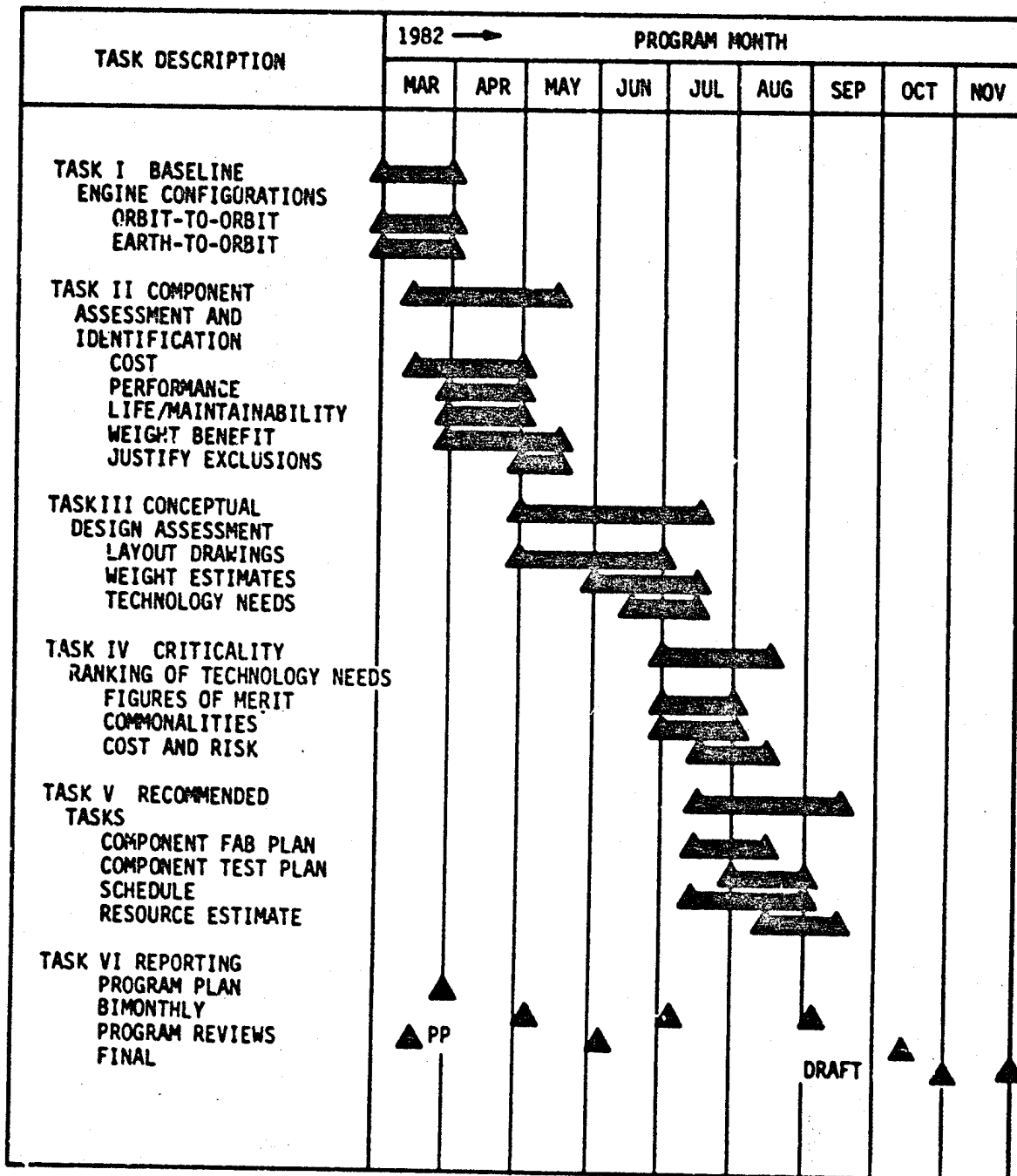


Figure 6. Major Milestone Schedule

III. TASK I - BASELINE ENGINE CONFIGURATIONS

A. OBJECTIVES

The objective of Task I was to establish baseline representative engine configurations for both orbit-to-orbit and earth-to-orbit engines. The task was limited to schematic descriptions of the selected engine systems and to general configurations and engine component requirements.

B. ENGINE SELECTIONS

After consideration of the three orbit-to-orbit point design studies (Ref. 1, 2, and 3), the 15,000-lbF Advanced Expander Cycle Engine (OTE) was selected to represent the orbit-to-orbit configuration. A layout of this engine is shown in Figure 7. Component layouts for the injector, chamber and nozzle, boost pump, main pump, and valves are given in Figures 8 through 14. These layouts, plus the corresponding component dimensions that were utilized in preparing the layout, provide the means for estimating the composites' impact on weight and structural integrity. A flow schematic for the OTE engine is shown in Figure 14A. A detailed component weight breakdown for the metallic OTE baseline engine is shown in Table II. This table also shows a preliminary estimate of what the engine would weigh if RPC's were substituted wherever possible.

A study of the earth-to-orbit engines described in Contracts NAS 8-33452 and NAS 8-32967 (Ref. 4 and 5, respectively) led to the selection of the 600,000-lbF LOX/LCH₄ (Cycle C - Gas Generator Cycle) engine to represent the earth-to-orbit configuration. A layout of this engine is shown in Figure 15. Layouts of the major components (turbopumps, injector, and gas generator, etc.) are available from Contract NAS 3-19727 and are shown in Figures 16 through 21. A flow schematic for the 600-K booster is shown in Figure 21A. A detailed component weight breakdown for the LOX/LCH₄ base-

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Figure 7. OTV Engine Layout (Sheet 2 of 3)

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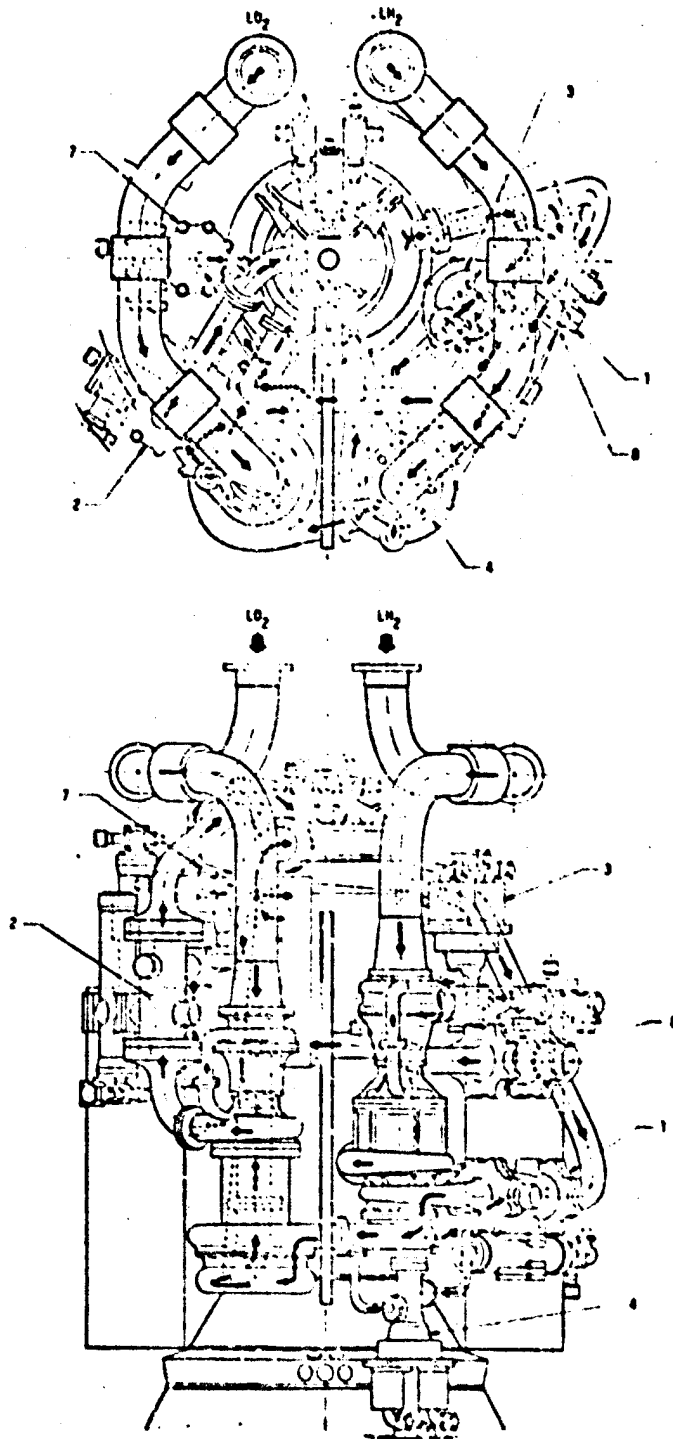


Figure 7. OTV Engine Layout (ALRC Dwg. No. 1193100) (Sheet 3 of 3)

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Figure 8. Igniter/Injector Assembly (ALRC Dwg No. 1191990)

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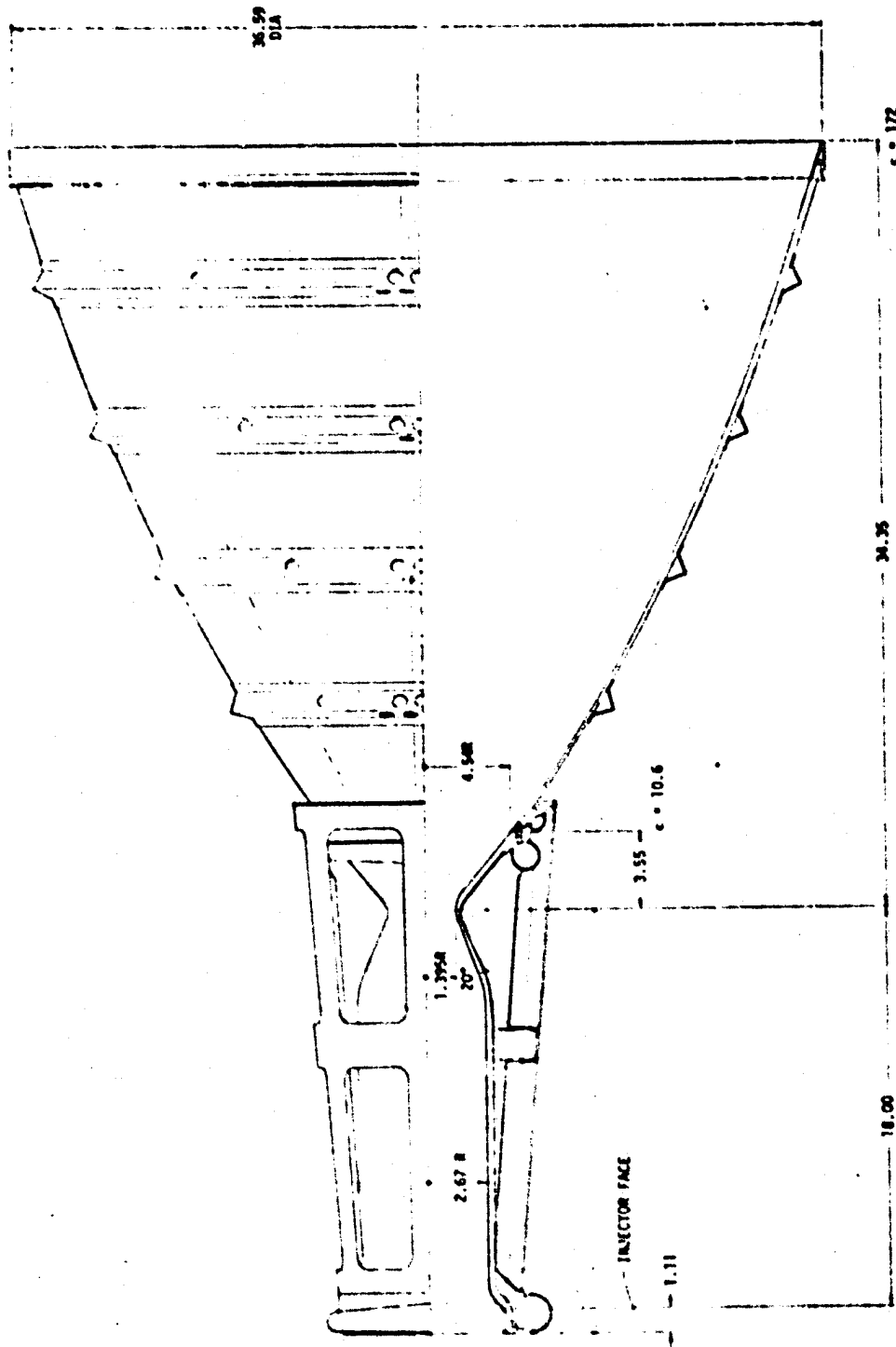


Figure 9. Chamber and Tube Bundle Nozzle (ALRC Dwg No. 1191991)

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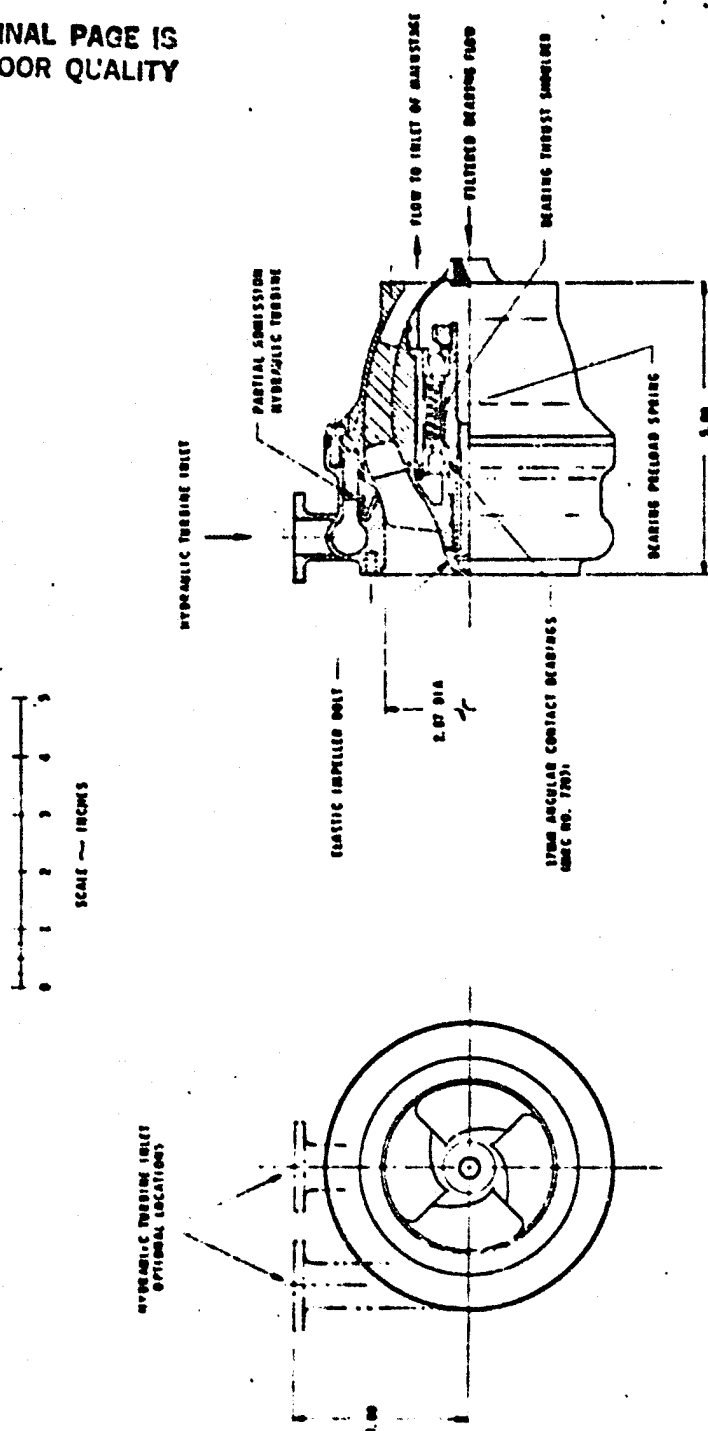


Figure 10. LO₂ Boost Pump (ALRC Dwg No. 1191994)

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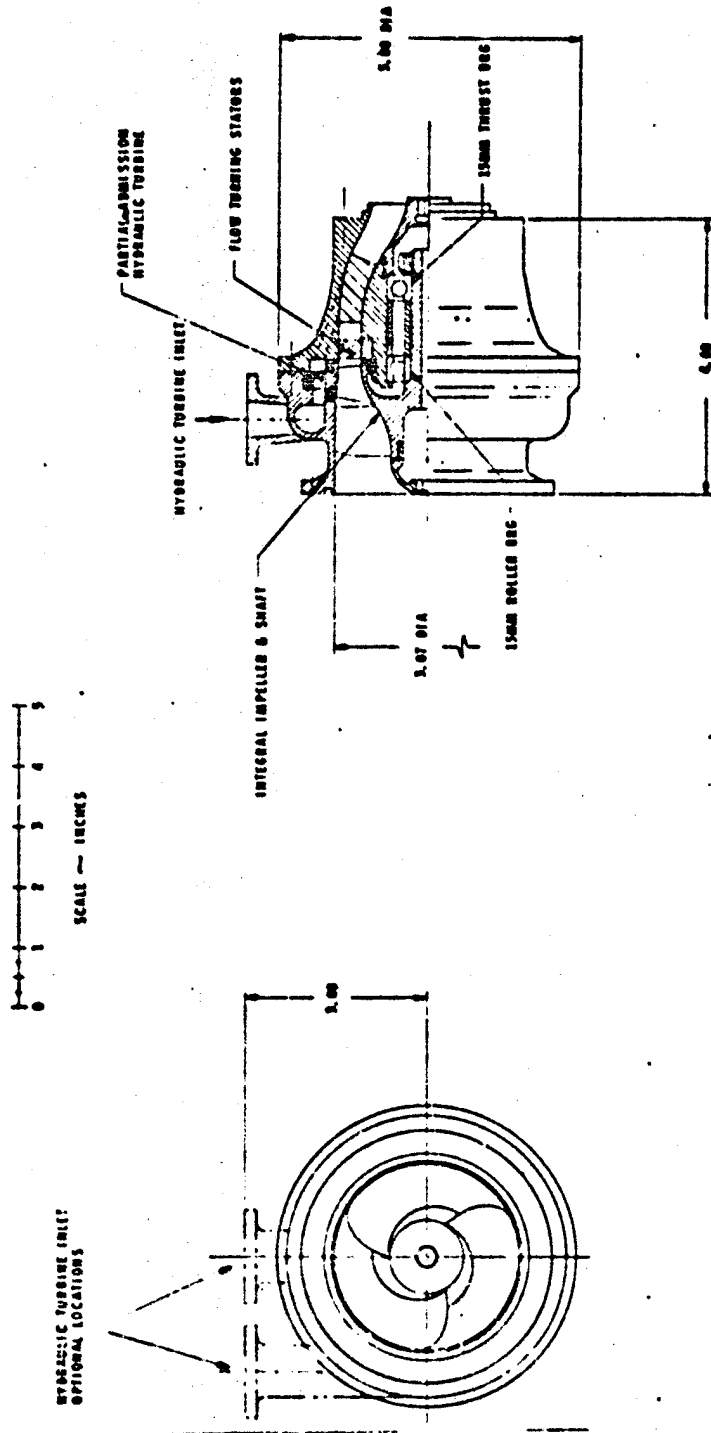


Figure 11. LO₂ Boost Pump (ALRC Dwg No. 1191996)

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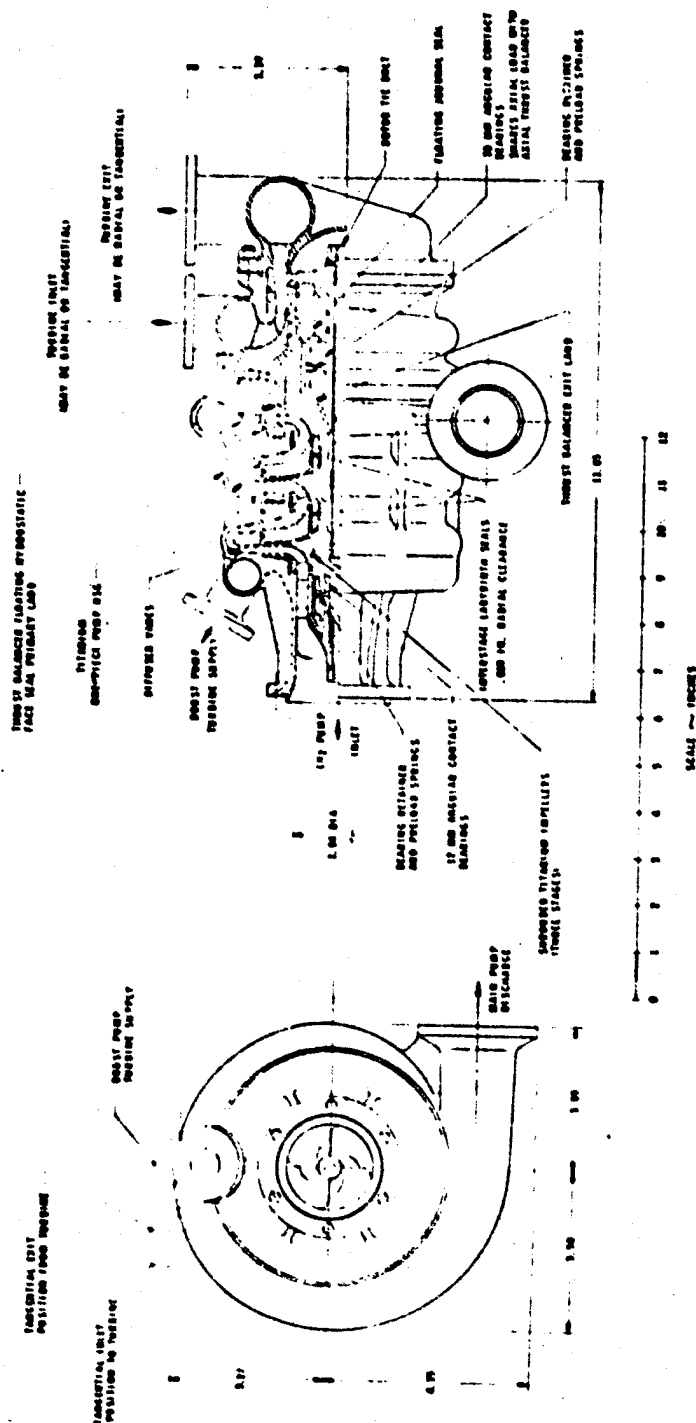


Figure 12. LH₂ TPA (ALRC Dwg No. 1191997)

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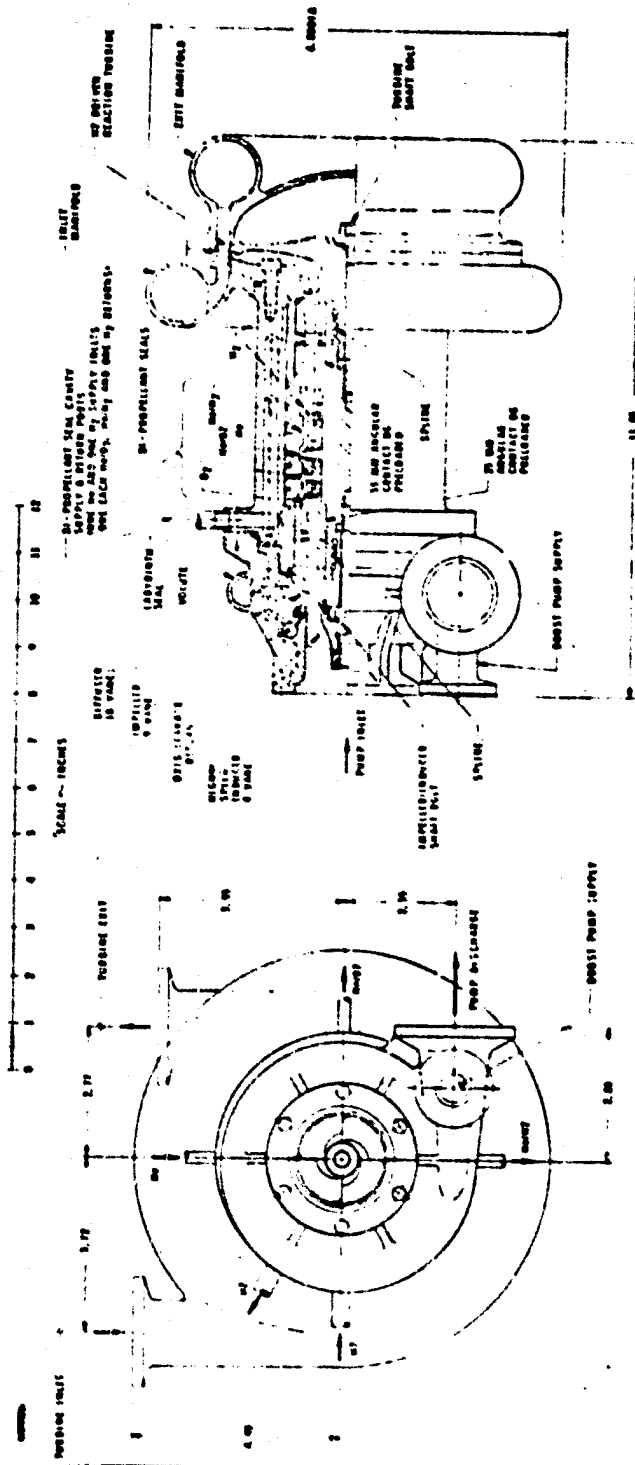


Figure 13. LO₂ TPA (ALRC Dwg No. 1191999)

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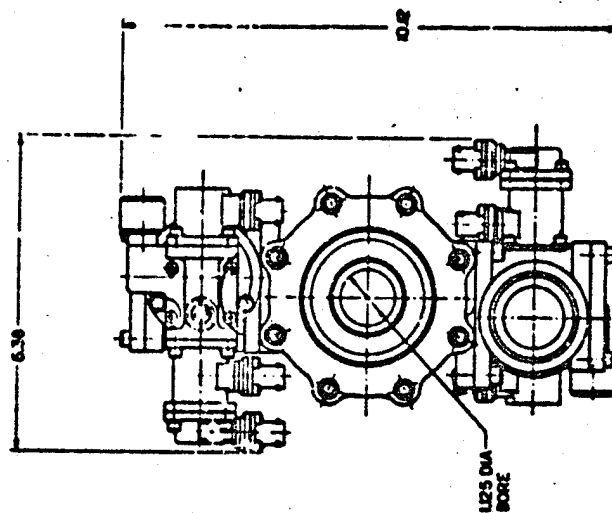
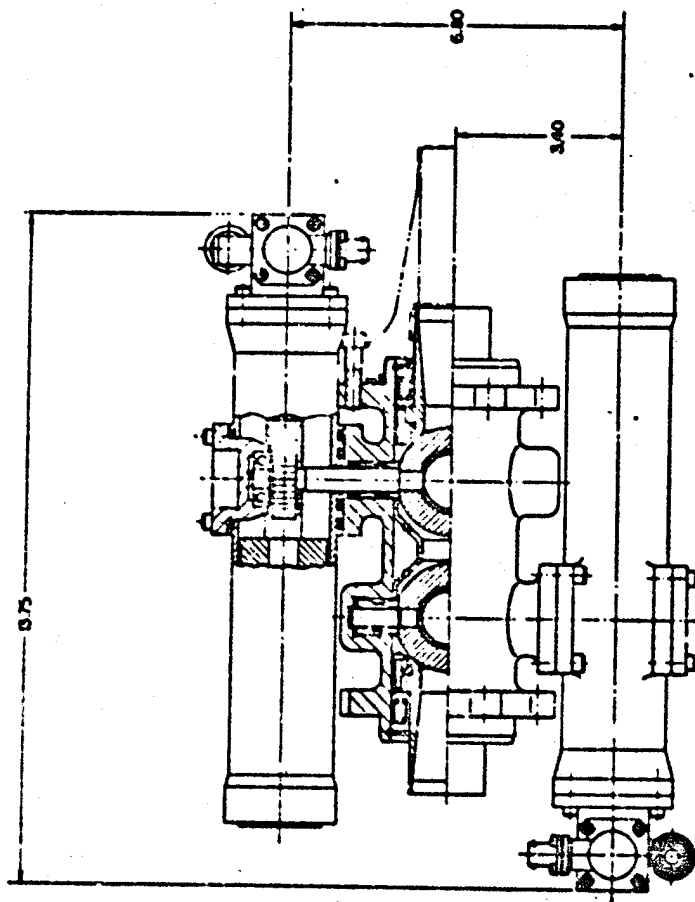
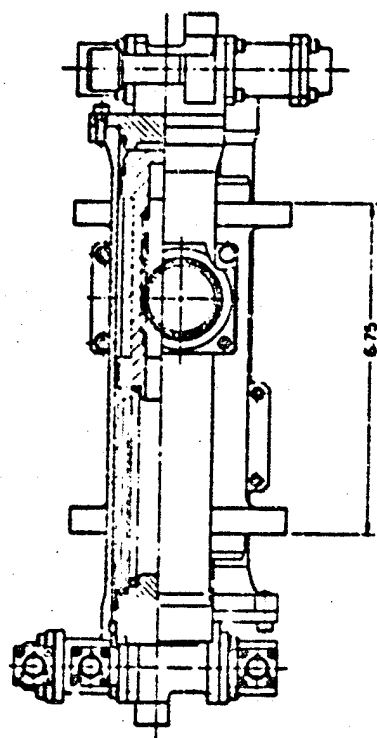


Figure 14. Shutoff Valve (ALRC Dwg No. 1193176)

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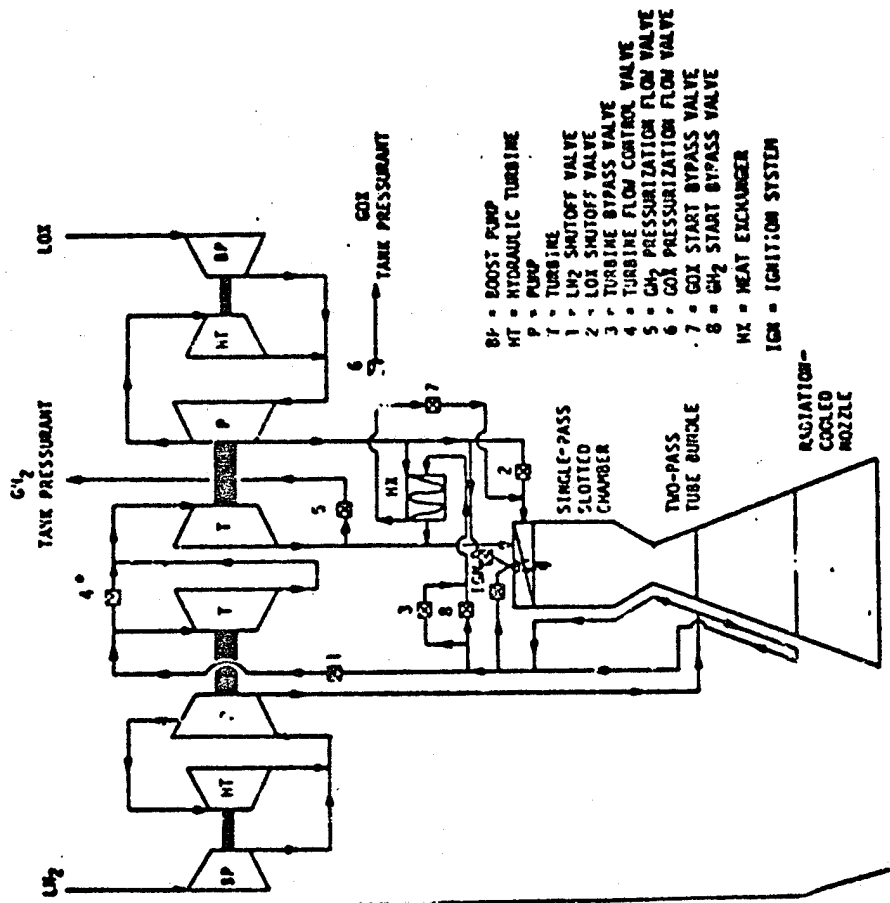


Figure 14A. OTV Flow Schematic

F = 15000 lbf
Pc = 1200 psia
Isp/VAC = 475.4 sec
O/F = 6.0
Expansion Ratio = 435:1
Oxidizer Main Pump Horsepower = 252.5 HP
Oxidizer Main Pump Discharge Pressure = 1470 psia
Fuel Main Pump Horsepower = 1022 HP
Fuel Main Pump Discharge Pressure = 2473 psia

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TABLE II
ADVANCED EXPANDER CYCLE ENGINE WEIGHT DATA

Page 1 of 4

<u>Engine Components</u>	<u>Current Weight</u>	<u>New Weight</u>	<u>Weight* Reduction</u>
Radiation-Cooled Nozzle	(80)	(80)	-
Valves and Actuators	(72.8)	(23.5)	(49.3)
Two Valve Bodies	10	2.6	7.4
Four Actuator Bodies	29	8.7	20.3
Actuator End Closures	7.8	2.2	5.6
Four Gates	5.0	1.8	3.2
Shafts	10	3.6	6.4
Gears	10	3.6	6.4
Springs	1	1	-
Nozzle Deployment System	(72)	(39.9)	32.1
Three Extension Shafts	24	4.9	19.1
Support Ring	27	14	13.0
Gear Box	-	-	-
Ball Screws	21	21	-
Flex Shafts	-	-	-
Combustion Chamber	(74.3)	(43.7)	30.6
Liner	20.4	20.4	-
Closeout	9.4	3.7	5.7
Manifolds	22.5	14	8.5
Support Structure	22.0	5.6	16.4
Nozzle-Tube Bundle	(38.4)	(34.4)	(4.0)
Tube Assembly	29.4	29.4	-
Four Reinforcing Rings	3	1.2	1.8
Manifold	6	3.8	2.2

NOTES:

- * Potential weight reduction with use of composite materials

ADVANCED EXPANDER CYCLE ENGINE WEIGHT DATA (Cont'd)

Page 2 of 4

<u>Engine Components</u>	<u>Current Weight</u>	<u>New Weight</u>	<u>Weight Reduction</u>
Propellant Lines	(37)	(17.4)	(19.6)
Tubes	9	3.8	5.2
Flanges	10	6	4
Flex Joints	18	7.6	10.4
Controller	(35)	(32.4)	(2.6)
Case	11	8.4	2.6
Add Other	24	24	-
Injector	(30.6)	(23.1)	(7.5)
Body	21	16	5
Face	1.0	1.0	-
Coaxial Elements	1.2	.5	.7
Manifold	5	3.8	1.2
Two Clevises	2.4	1.8	.6
LOX TPA	(25.1)	(15.0)	(10.1)
Pump Housing	5.4	2.4	3
Seal Housing	7.0	5.3	1.7
Turbine Housing	4.0	1.8	2.2
Impeller	.2	.1	.1
Shaft	2.0	.9	1.1
Turbine	4.0	2	2
Bearing	2.5	2.5	-
LH ₂ TPA	(21.5)	(9.8)	(11.7)
LH ₂ Inlet Housing	4.0	1.8	2.2
Pump Housing	8.5	3.8	4.7
Inducer	.1	.05	.05
Impellers	3.0	1.5	1.5
Turbine Exit Housing	3.7	1.4	2.3

ADVANCED EXPANDER CYCLE ENGINE WEIGHT DATA (Cont'd)

Page 3 of 4

<u>Engine Components</u>	<u>Current Weight</u>	<u>New Weight</u>	<u>Weight Reduction</u>
LH ₂ TPA (Cont'd)			
Shaft	1.4	.7	.7
Turbines	.6	.3	.3
Bearings	.2	.2	-
Misc. Valves and Pneumatic Package	[12.6]	[12.6]	-
Ignition System	[9.2]	[9.2]	-
LH ₂ Boost Pump	(8.6)	(3.9)	(4.7)
Turbine-Impeller Housing	3.6	1.6	2.0
Exit Housing	4.1	1.8	2.3
Turbine Impeller	.3	.15	.15
Impeller Bolt	.1	.1	-
Shaft	.4	.18	.22
Bearings	.08	.08	-
LOX Boost Pump	(5.5)	(2.5)	(3.0)
Turbine-Impeller Housing	2.4	1.05	1.35
Exit Housing	2.7	1.2	1.5
Impeller Shaft	.3	.15	.15
Bearings	.08	.08	-
Heat Exchanger	(5)	(2.5)	(2.5)
Outer Shell	3.5	1.75	1.75
Inner Shell	1.5	.75	.75
Gimbal	(3.3)	(2.1)	(1.2)
Thrust Pad	1.2	.54	.66
Thrust Mount	.7	.49	.21
Cap	.2	.15	.05
Shaft	.8	.58	.22
Monoball	.2	.15	.05
Fasteners	.2	.2	-

ADVANCED EXPANDER CYCLE ENGINE WEIGHT DATA (Cont'd)

Page 4 of 4

<u>Engine Components</u>	<u>Current Weight</u>	<u>New Weight</u>	<u>Weight Reduction</u>
Miscellaneous	[37]	[37]	-
Electrical Harness	12.5	12.5	-
Service Lines	6.5	6.5	-
TPA Protective Bulkhead	.4	.4	-
Attachment Hardware	15.0	15.0	-
Instrumentation	2.6	2.6	-
TOTAL WEIGHT	567.9	389	178.9

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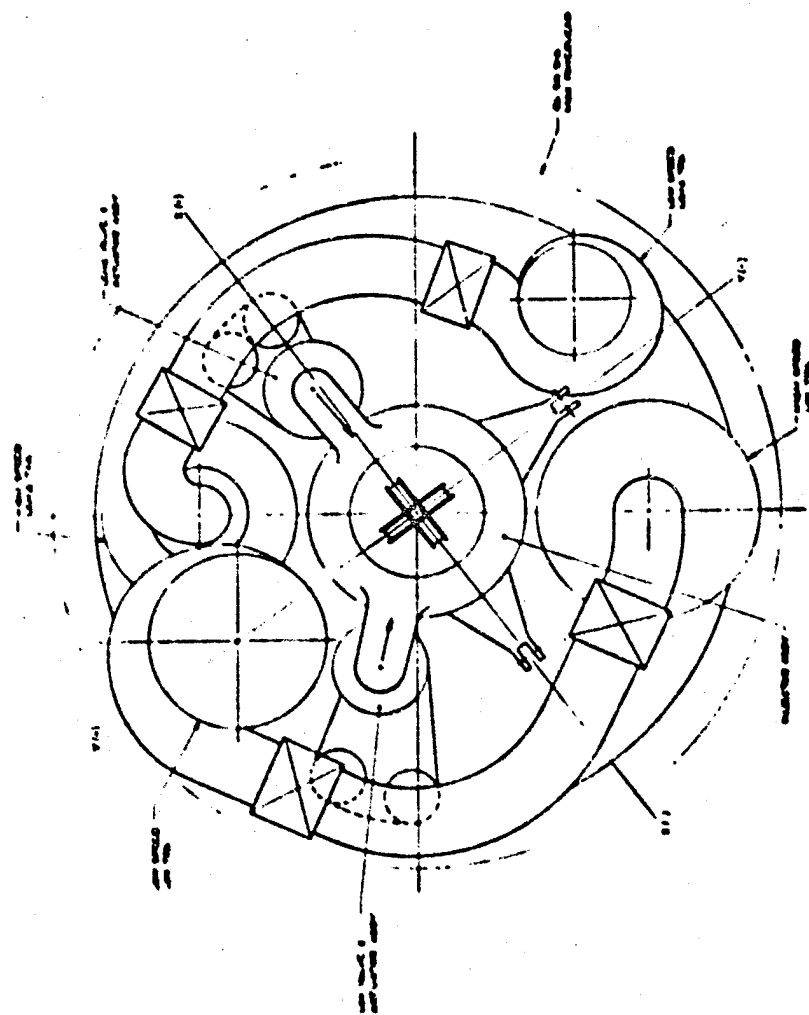


Figure 15. LOX/LCH₄ Engine Layout (Sheet 1 of 2)

Technical drawing of a mechanical assembly, likely a pump or engine component, showing a cross-section view. The drawing includes various labeled parts and dimensions. Key components include a large cylindrical housing, a central shaft, and a complex internal mechanism. Dimensions are provided for various parts, including a 100.00 inch diameter, a 10.00 inch length, and a 10.00 inch diameter. The drawing is oriented vertically with the top of the assembly at the bottom of the page.

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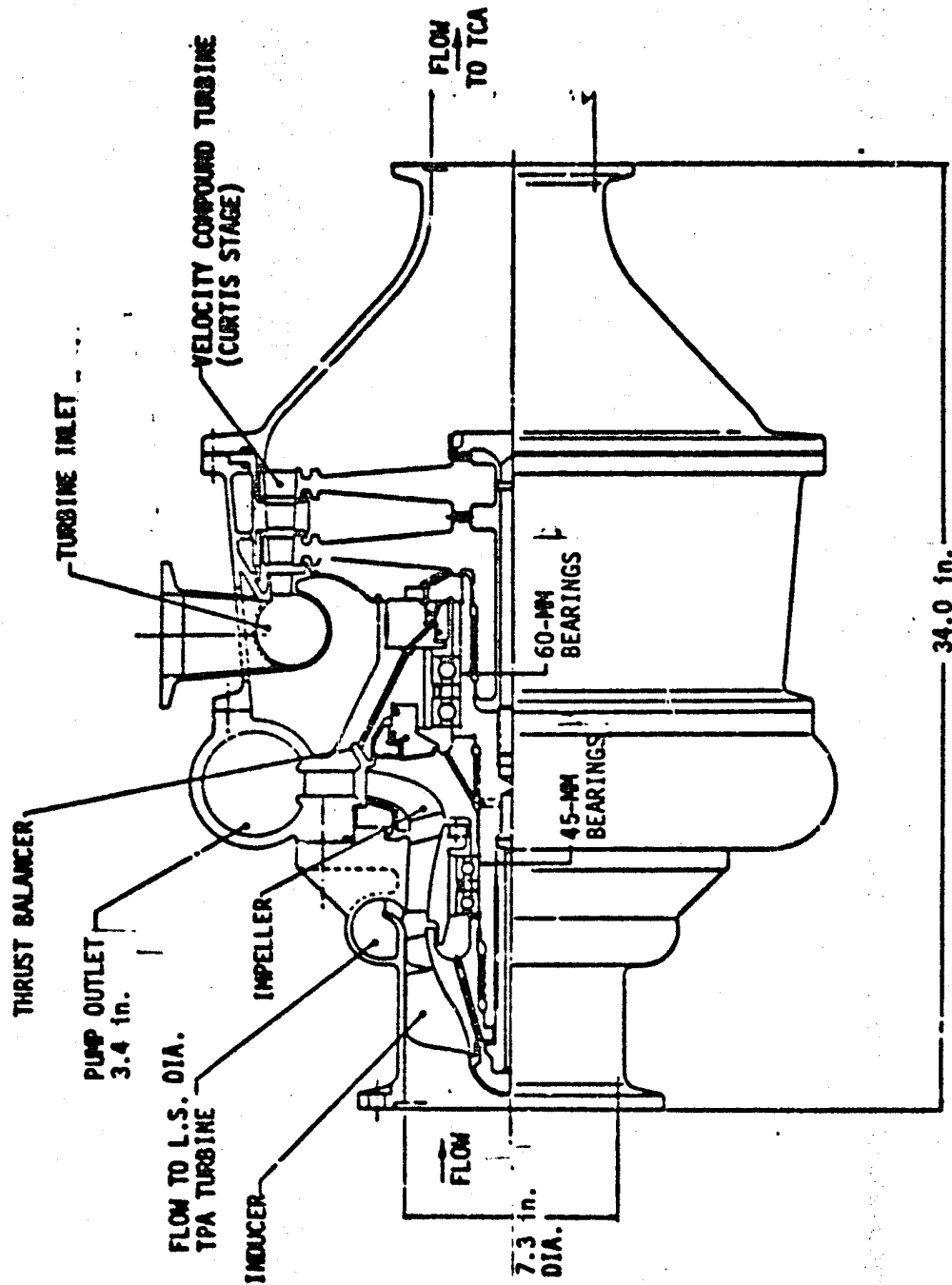


Figure 16. High-Speed LCH₄ TPA

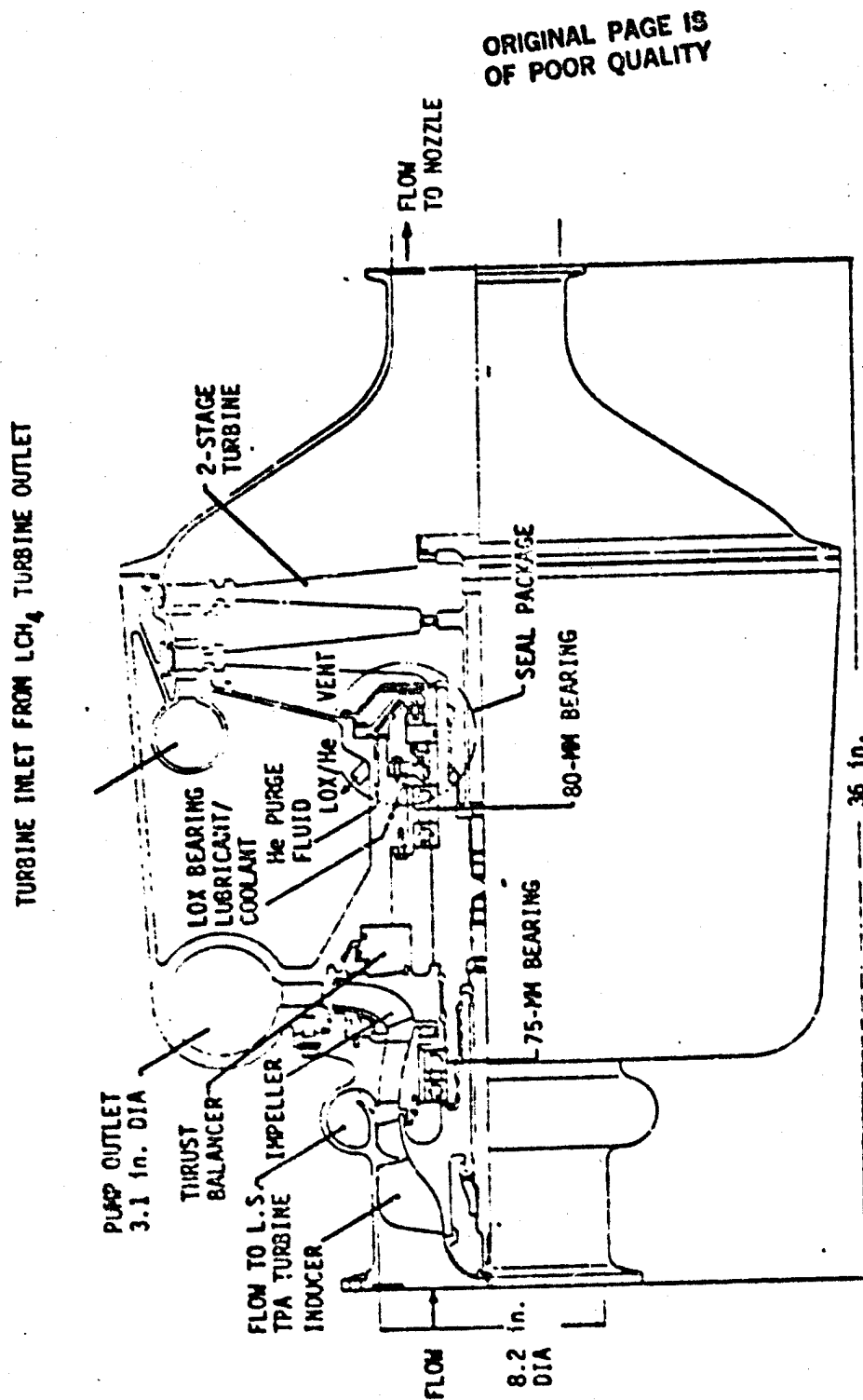


Figure 17. High-Speed LOX TPA

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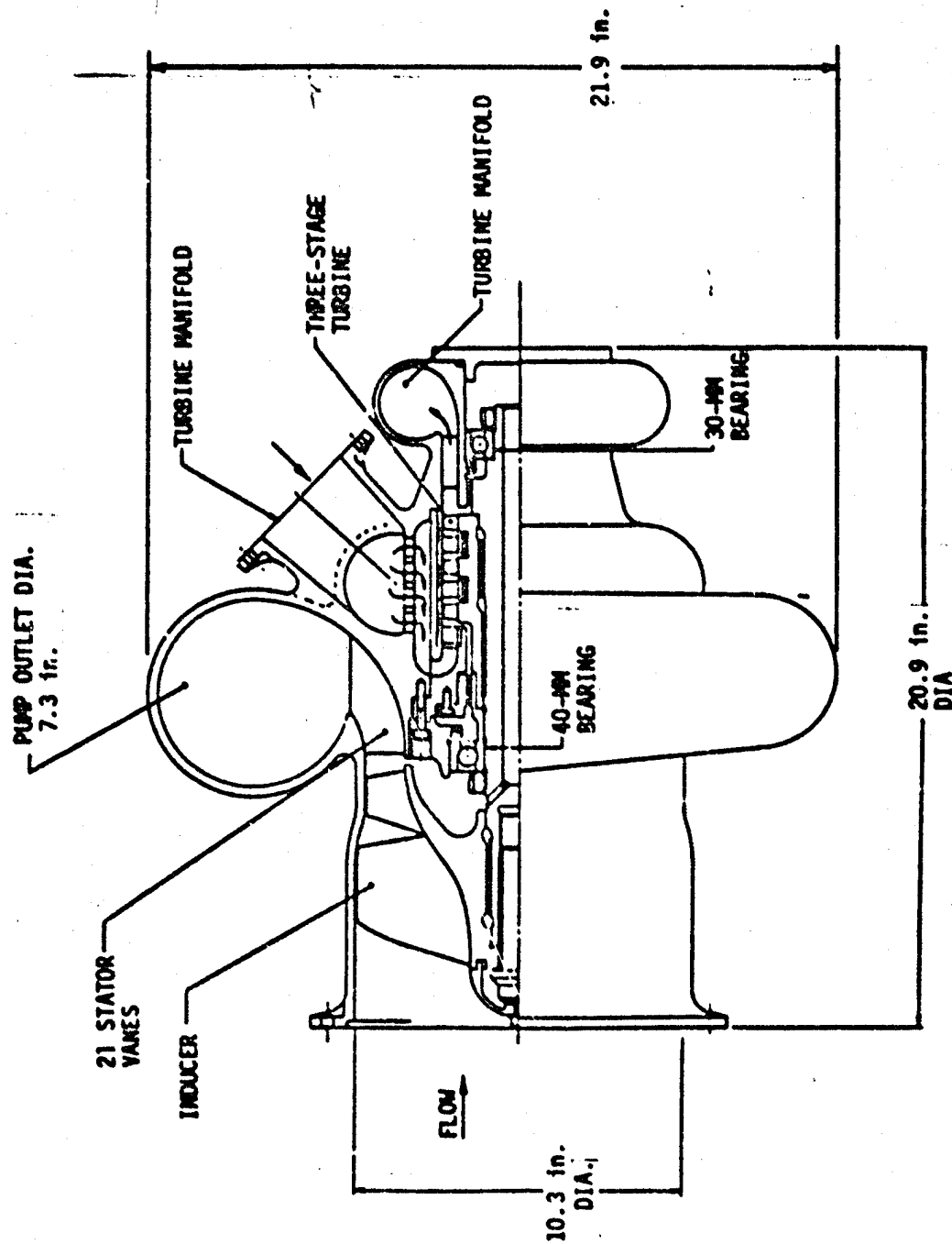


Figure 18. Baseline Mode 1 Dual-Fuel and Alternate Mode 1 Low-Speed
BP-1 TPA

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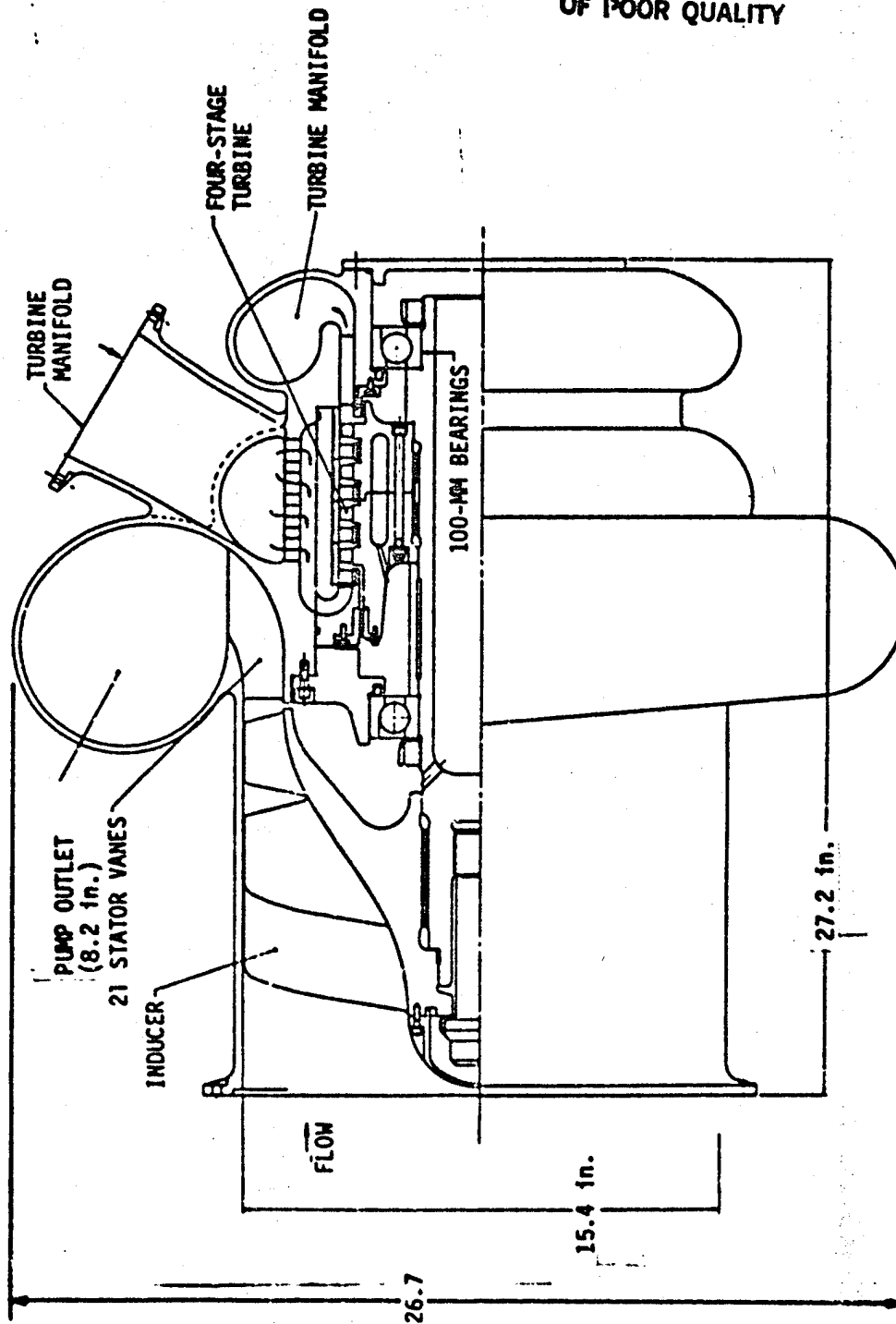


Figure 19. Baseline Mode 1 Dual-Fuel and Alternate Mode 1 Low-Speed
LOX TPA

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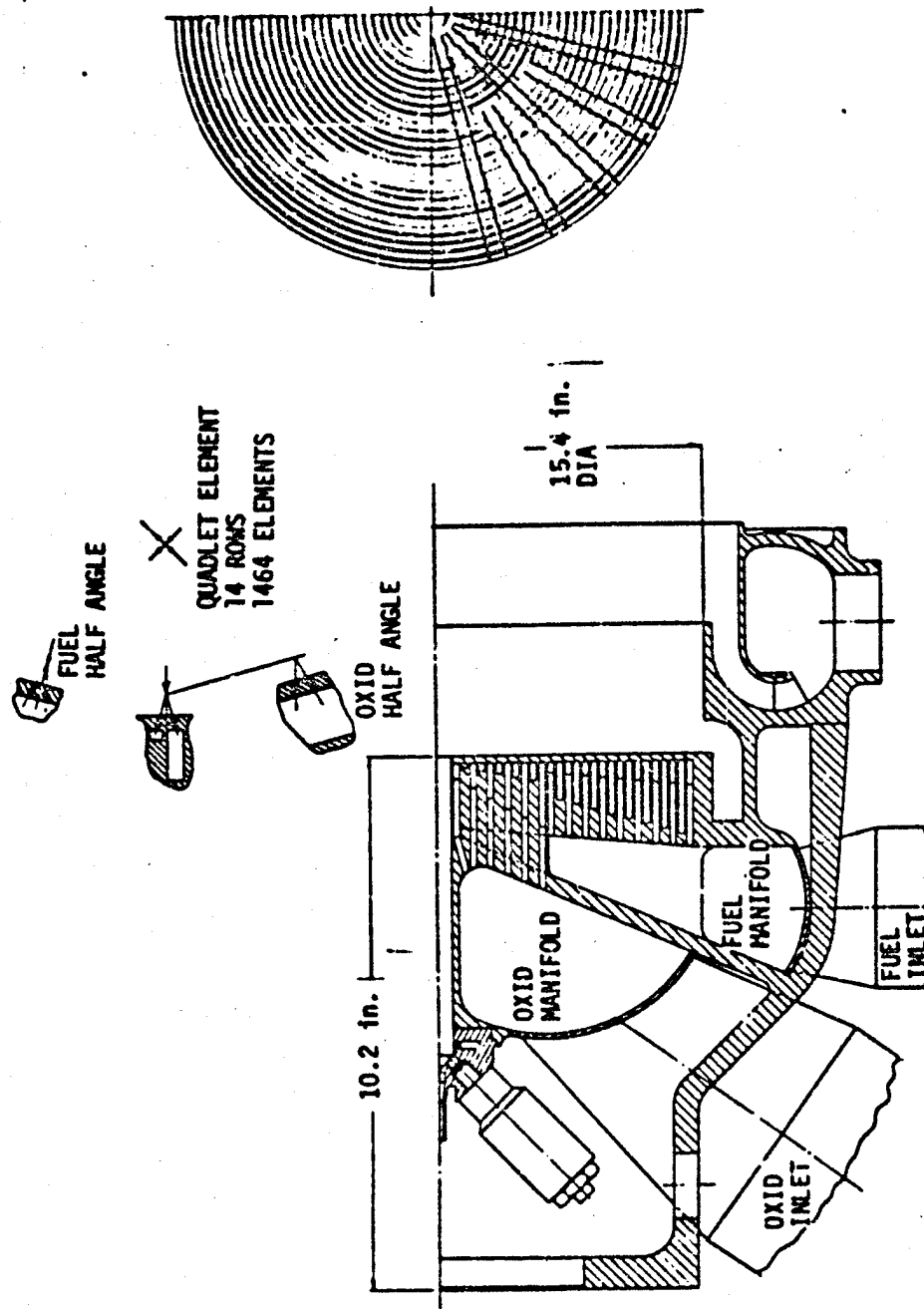


Figure 20. Alternate Mode 1 Gas Generator Cycle
Engine Thrust Chamber Injector.

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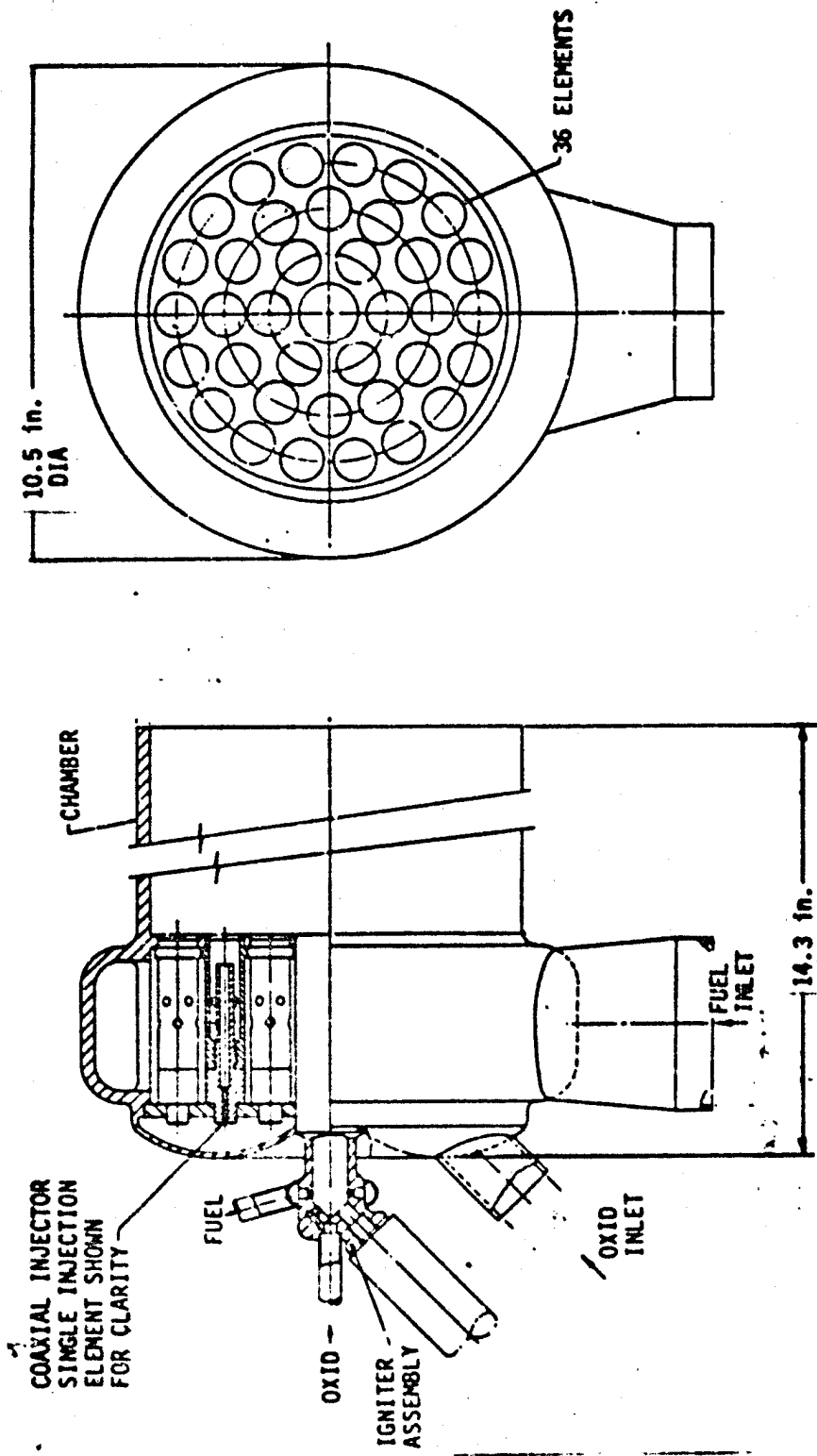
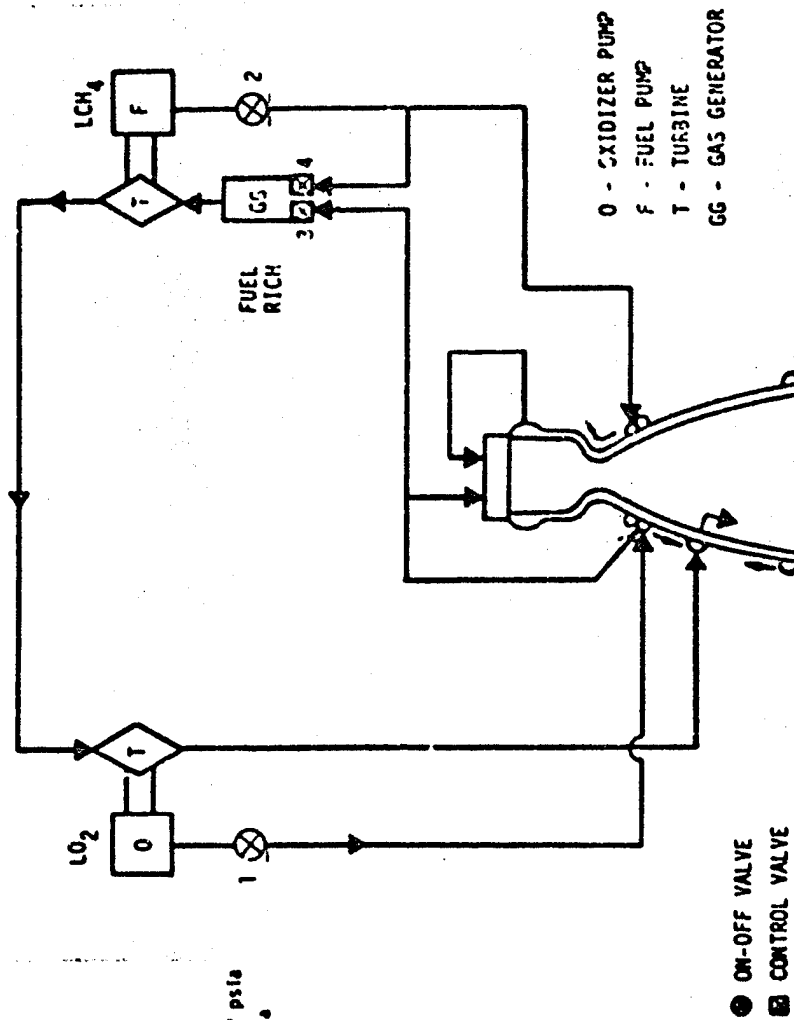


Figure 21. Alternate Mode 1 Coaxial Gas Generator

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$F = 600K \text{ lbf}$
 $P_c = 4300 \text{ psia}$
 $I_{sp} = 309 \text{ sec}$
 $I_{sp} VAC = 345.8 \text{ sec}$
 $O/F_{TCA} = 3.5$
 $O/F_{GG} = 0.40$
 $\text{Expansion Ratio} = 56.5$
 $\text{Oxidizer Main Pump Discharge Pressure} = 5262 \text{ psia}$
 $\text{Fuel Main Pump Discharge Pressure} = 7953 \text{ psia}$

Figure 21A. LOX/LCH₄ Engine Flow Schematic

III. B. Engine Selections (cont.)

line engine is shown in Table III. (The table includes estimates for engine weight using composites wherever possible.) The majority of the component weights shown in Tables II and III were based only on scaling equations or preliminary drawing volumes. The ten components selected for further study during Task III (Section V of this report) were stress-analyzed and drawn in detail to obtain more precise weights. (See Table VI.)

C. COMPONENT REQUIREMENTS DATA SHEETS

After selecting the two baseline engine configurations, physical requirements for the major engine components were documented on "Component Requirement Sheets." An example of a "Component Requirements Sheet" for the oxidizer TPA on the LOX/LCH₄ engine is shown in Figure 22. The remainder of these data sheets is contained in Appendix A. This evaluation of each component's physical characteristics (i.e., thrust, Isp, temperature, pressure, weight, etc.) laid the groundwork for beginning Task II.

TABLE III
LOX/LCH₄ CYCLE C ENGINE WEIGHT DATA

Page 1 of 4

<u>Engine Components</u>	<u>Current Weight</u>	<u>New Weight</u>	<u>Weight Reduction</u>
LO ₂ TPA	(895)	(624.2)	(270.8)
Inducer Housing	122	90.7	31.3
Inducer	84	41.7	42.3
Impeller	51	25.4	25.6
Impeller Housing	144	49	95
Turbine Inlet Housing	66	66	-
Turbine Vanes	62	62	-
Turbine Rotors	217	217	-
Shaft	145	68.4	76.6
Bearings	4	4	-
CH ₄ TPA	(661)	(396.8)	(264.2)
Inducer Housing	79	52.4	26.6
Inducer	63	19.9	43.1
Impeller	40	19.9	20.1
Impeller Housing	163	34	129
Turbine Inlet Housing	46	46	-
Turbine Vanes	42	42	-
Turbine Rotors	138	138	-
Shafts	86	40.6	45.4
Bearings	2.2	2.2	-
Add Miscellaneous	1.8	1.8	-
Injector	(611)	(477)	(134)
Body	373	282	91
Face	17	17	-
LOX Manifold Cover	33	25	8
Fuel Manifold Cover	33	25	8
Housing	51	24	27
Add Misc	4	4	-
Acoustic Cavity	100	100	-

LOX/LCH₄ CYCLE C ENGINE WEIGHT DATA (Cont'd)

Page 2 of 4

<u>Engine Components</u>	<u>Current Weight</u>	<u>New Weight</u>	<u>Weight Reduction</u>
High-Pressure Lines	(384)	(334.4)	(49.6)
Tubes (1)	30	12.8	17.2
Tubes (2)	178	178	-
Tubes (3)	40	40	-
Flanges (1)	80	47.6	32.4
Flanges (2)	16	16	-
Flex Joints	40	40	-
Combustion Chamber	(364)	(228.6)	(135.4)
Liner	154	154	-
Closeout	61	24	37
Manifolds	50	11	39
Support Structure	99	39.6	59.4
Nozzle	(328)	(220)	(108)
Tube Assembly	109	109	-
Manifold	93	58.5	34.5
Manifold	49	31	18
Reinforcing Rings	22	10.5	11.5
Jacket	55	11	44
LO ₂ Boost Pump	(311)	(176)	(135)
Housing Hybrid	193	97	96
Inducer Bolt	7	7	-
Turbine	12	6	6
Shaft	60	27	33
Bearings	1	1	-
Add Miscellaneous	38	38	-

LOX/LCH₄ CYCLE C ENGINE WEIGHT DATA (Cont'd)

Page 3 of 4

<u>Engine Components</u>	<u>Current Weight</u>	<u>New Weight</u>	<u>Weight Reduction</u>
Low-Pressure Lines	(253)	(113)	(140)
Tubes (1)	12		
Tubes (2)	19		
Tubes (3)	54	72	113
Tubes (4)	100		
Flanges	68	41	27
Gimbal	(204)	(133.6)	(70.4)
Seat	29	13	16
Body	166	114	52
Block	7	5	2
Shaft	2	1.6	.4
Miscellaneous	[174]	[174]	-
LOX Valves	(156)	(117.1)	(38.9)
Bodies	80	60.9	19.1
Balls	38	25	13
Shafts	13	6.2	6.8
Miscellaneous	25	25	-
Pressurization System	[138]	[138]	-
CH ₄ Valves	(134)	(110.9)	(23.1)
Bodies	70	64	6
Balls	33	21.7	11.3
Shafts	11	5.2	5.8
Miscellaneous	20	20	-
Controller	(130)	(120)	(10)
Housing	42	32	10
Add Other	88	88	-

LOX/LCH₄ CYCLE C ENGINE WEIGHT DATA (Cont'd)

Page 4 of 4

<u>Engine Components</u>	<u>Current Weight</u>	<u>New Weight</u>	<u>Weight Reduction</u>
Fuel Boost Pump	(103)	(62.5)	(40.5)
Housing	62	42	20
Inducer	15	7.5	7.5
Turbine	4	2	2
Inducer Bolt	.5	.5	-
Shaft	21	10	11
Bearings	.3	.3	-
Add Miscellaneous	.2	.2	-
Interpropellant Seal	[90]	[90]	-
Gas Generator	(76)	(52.8)	(23.2)
Injector Body	8	6	2
Manifold	13	9	4
Dome	5	3.3	1.7
Chamber	25	25	-
Elements	25	9.5	15.5
Ignition System	[40]	[40]	-
Hot-Gas Manifold	[23]	[23]	-
TOTAL WEIGHT	5075	3632	1443

BASELINE ENGINE: LOX/LCH₄ ENGINE (CYCLE C)

COMPONENT: OXIDIZER MAIN TPA

PUMP PRESSURE = 5262 PSIA

TURBINE PRESSURE = 4200 PSIA

T_{PUMP} = 166°R

T_{TURB} = 1860°R

W_{PUMP} = 1395.5 lbm/SEC

W_{TURB} = 156.61 lbm/SEC

ENVELOPE = 26.9 IN. (DIAM) x 36 IN. (LENGTH)

D_{IN} = 8.2 IN.

D_{OUT} = 3.1 IN.

WEIGHT = 895 lbm

MATERIALS:

a) SHAFT	A-286
b) IMPELLER	INCONEL 718
c) PUMP AND TURBINE HOUSING	ARMCO NITRONIC 50
d) INDUCER HOUSING	INCONEL 718
e) TURBINE	INCONEL 718
f) BOLTS (PUMP)	A-286
g) BOLTS (TURBINE)	WASPALLOY
h) BEARINGS	CRES 440C

Figure 22. Sample "Component Requirements" Form

IV. TASK II - COMPONENT ASSESSMENT AND IDENTIFICATION

A. OBJECTIVES

Task II involved the assessment of all baseline engine components from Task I and the identification of those components which could potentially benefit the most from composite material substitution. Figure 23 displays a schematic which outlines the steps taken in performing this task:

The basic contractual ground rules from NASA-MSFC mandated that the selections for composite substitution be based primarily on weight savings, and secondarily on cost, life, and maintainability. It was also desired that the selections address a variety of new technology needs and not merely represent a direct application of existing airframe composite technology to simple components such as frames and gimbal rings.

B. COMPOSITE PROPERTIES AND FABRICATION PROCESSES

The initial effort in Task II was to gather and organize information pertinent to the uses and limitations of composite materials.

Material properties for the most commonly used reinforced plastic composites (RPC's) are contained in Appendix B. The material properties data were obtained from one of the following sources: 1) vendor data, 2) Air Force Composite Design Guide (Ref. 6), 3) technical seminars, 4) textbooks (Ref. 7), and 5) literature search of technical papers. Appendix C contains similar material properties data for the most commonly used metal matrix composites (MMC).

A short summary of composite fabrication processes, reinforcement characteristics, matrix characteristics, and material properties is shown in Figure 24 through 27, respectively. These figures are included for the

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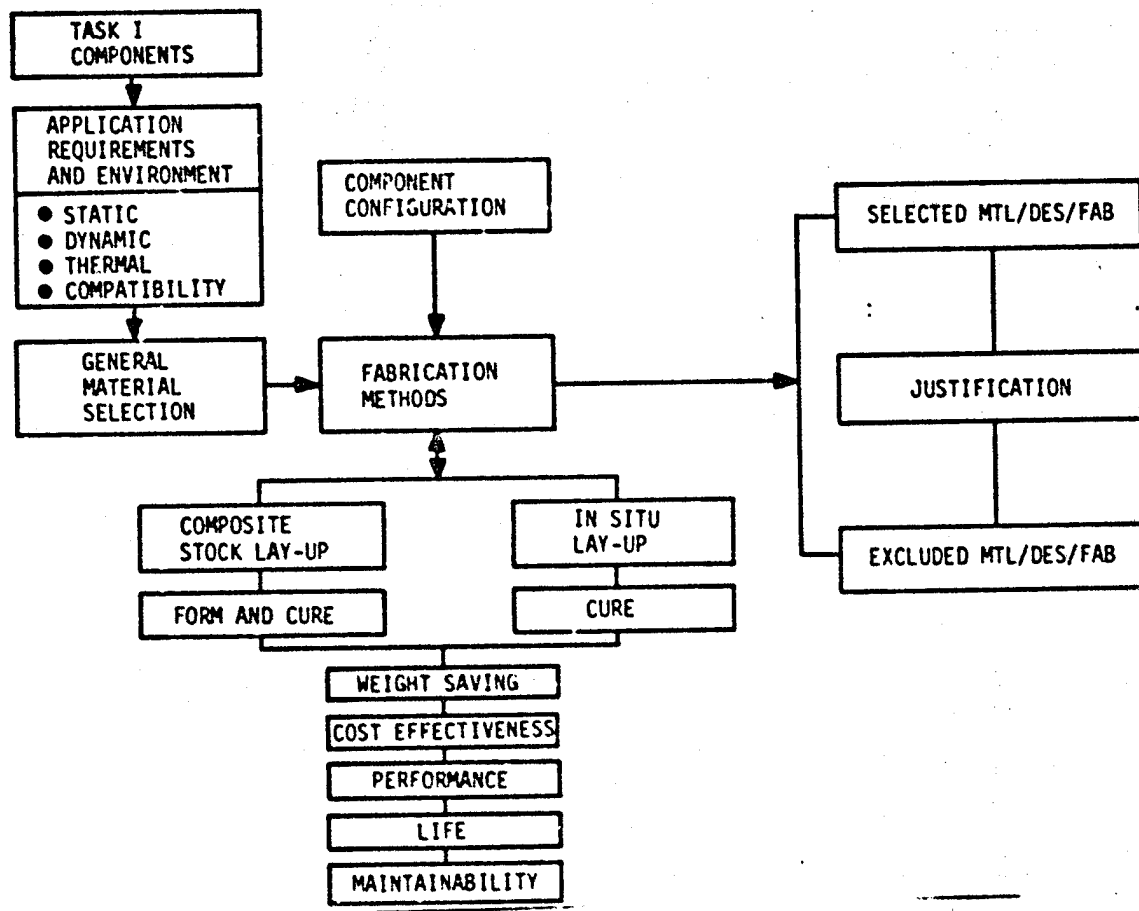


Figure 23. Task II Schematic

- **COMPRESSION MOLDING - RESIN IMPREGNATED FIBER MATERIAL (CALLED PREPREG OR MOLDING COMPOUND) IS PLACED IN A MATCHED DIE MOLD AND HEAT AND PRESSURE ARE USED TO FORM AND CURE THE PART. FINISHED DETAIL IS GOOD AND INSERTS AND LINERS CAN BE INTEGRALLY ATTACHED**
(AUTOMOTIVE AND ELECTRONIC STRUCTURAL PARTS)
- **AUTOClave MOLDING - PREPREG IS PLACED ON A FORMING TOOL ALONG WITH A BLEEDER SYSTEM. THE LAYED UP MATERIALS ARE COVERED WITH A PLASTIC FILM AND SUBJECTED TO HEAT AND HIGH PRESSURE IN AN AUTOCLAVE. (EXAMPLE - ABLATIVE CHAMBER)**
- **VACUUM BAG MOLDING - SIMILAR TO AUTOCLAVE MOLDING EXCEPT THAT AMBIENT PRESSURE IS USED IN PLACE OF AUTOCLAVE PRESSURE. (NON-STRUCTURAL AIRCRAFT PARTS)**
- **PULTRUSSION - PREPREG MOLDING MATERIAL IS DRAWN THROUGH A DIE IN WHICH RAPID CURING OCCURS. THIS PROCESS IS LIMITED TO MAKING STRAIGHT PIECES HAVING A CONSTANT CROSS SECTION (AUTOMOTIVE DRIVE SHAFTS)**
- **REACTION INJECTION MOLDING - PREFORMED FIBER MATERIAL IS PLACED IN A MOLD CAVITY. RESIN IS INJECTED INTO THE MOLD WHERE IMPREGNATION AND MOLDING OCCUR (AUTOMOTIVE AND ELECTRONIC STRUCTURAL PARTS)**

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Figure 24. Fabrication Processes

- KEVLAR - A SYNTHETIC ORGANIC FIBER WITH A VERY HIGH TENSILE STRENGTH AND MODULUS. ON THE OTHER HAND IT DISPLAYS POOR PROPERTIES IN COMPRESSION AND HAS PROBLEMS WITH MATRIX ADHESION TO THE KEVLAR FIBERS. GENERALLY LIMITED TO TENSION APPLICATIONS
- GRAPHITE - MADE FROM A SYNTHETIC ORGANIC FIBER AS A RESULT OF A STRESS - GRAPHITIZATION PROCESS. IT POSSES HIGH TENSILE AND COMPRESSIVE PROPERTIES
- FIBERGLASS - MADE FROM SILICA AND WIDELY USED AS A REINFORCEMENT IN COMPOSITE MATERIALS. NOT AS STRUCTURALLY EFFICIENT AS THE ORGANIC FIBERS, BUT VERY COST EFFECTIVE
- BORON - FIBER IS MANUFACTURED BY VAPOR DEPOSITION OF BORON ON A TUNGSTEN WIRE FILAMENT. CHARACTERIZED BY A HIGH MODULUS THAT SUITS IT FOR USE IN BOTH RESIN MATRIX AND METAL MATRIX COMPOSITES. VERY EXPENSIVE

Figure 25. Reinforcement Characteristics

- EPOXY - WIDELY USED BECAUSE OF ITS CONVENIENT TRANSFORMATION FROM A LIQUID TO A PLASTIC SOLID AND BECAUSE OF ITS ABILITY TO ADHERE TO A WIDE VARIETY OF REINFORCEMENTS. EPOXY MATRICES ARE ADVERSELY AFFECTED BY EXPOSURE TO RADIATION, HIGH TEMPERATURE, HUMIDITY, AND CERTAIN CHEMICALS
- POLYIMIDE RESINS - SIGNIFICANTLY LESS CONVENIENT TO USE IN COMPOSITE MATERIALS THAN EPOXIES. LESS AFFECTED BY HIGH TEMPERATURE AND CHEMICAL EXPOSURE
- ALUMINUM - DIFFICULT TO PRODUCE AND IS STRUCTURALLY LESS EFFICIENT THAN THE PLASTIC COMPOSITES. ON THE PLUS SIDE, ALUMINUM HAS A HIGHER TEMPERATURE LIMIT AND IS LESS AFFECTED BY CHEMICAL FACTORS BECAUSE OF ITS IMPERMEABILITY
- CARBON - VERY DIFFICULT TO PRODUCE AND VERY EXPENSIVE. ITS STRUCTURAL EFFICIENCY AT VERY HIGH TEMPERATURES IS UNMATCHED

Figure 26. Matrix Characteristics

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	TEMPERATURE LIMIT	SPECIFIC TENSILE STRENGTH	SPECIFIC STIFFNESS	SPECIFIC COMPRESSION	IN PLANE SHEAR	THERMAL EXPANSION	VAPOR PERMEATION	COST	COMMENTS
KEVLAR EPOXY	350°F	HIGHEST	MODERATE	LOWEST	LOWEST	LARGE (TRANS) SMALL (FIBER DIRECTION)	HIGH	LOW	USED PRIMARILY IN PRESSURE VESSELS
GRAPHITE EPOXY	350°F	HIGH	HIGH	HIGH	HIGH	LARGE (TRANS) SMALL (FIBER DIRECTION)	HIGH	HIGH	STIFFNESS APPLICATIONS
FIBERGLASS EPOXY	350°F	HIGH	LOW	MODERATE	HIGH	LARGE IN BOTH DIRECTIONS	HIGH	LOWEST	MOST WIDELY USED, NON-STRUCTURAL APPLICATIONS
HYBRID GRAPHITE KEVLAR EPOXY	350°F	HIGH	HIGH	MODERATE	LOW	LARGE (TRANS) SMALL (FIBER DIRECTION)	HIGH	MODERATE	USED PRIMARILY IN PRESSURE VESSELS
HYBRID GRAPHITE FIBERGLASS EPOXY	350°F	HIGH	MODERATE	MODERATE	HIGH	LARGE IN BOTH DIRECTIONS	HIGH	LOW	USED EXTENSIVELY IN AIRCRAFT SECONDARY STRUCTURE
GRAPHITE EPOXY/METAL LAMINATION	350°F	MODERATE	MODERATE	HIGH	HIGH	LARGE (TRANS) SMALL (FIBER DIRECTION)	LOW	HIGH	HIGH BEARING STRENGTH
CARBON-CARBON	4000°F	LOW	LOW	LOW	LOW	SMALL IN BOTH DIRECTIONS ("CONTRACTION")	HIGH	VERY HIGH	HIGH TEMPERATURE APPLICATIONS, BUT VERY EXPENSIVE NON-OXIDIZING
BORON EPOXY	350°F	HIGH	HIGH	HIGH	HIGH	MODERATE (FIBER) LARGE (TRANSVERSE)	HIGH	VERY HIGH	USED IN AIRCRAFT PRIMARY STRUCTURE
BORON POLYIMIDE	550°F	HIGH	HIGH	HIGH	HIGH	MODERATE (FIBER) LARGE (TRANS)	HIGH	VERY HIGH	USED IN HIGH PERFORMANCE AIRCRAFT
BORON ALUMINUM	700°F	LOW	MODERATE	LOW	MODERATE	MODERATE IN BOTH DIRECTIONS	LOW	HIGH	R & D APPLICATIONS

Figure 27. Properties of Various Components

IV. B. Composite Properties and Fabrication Processes (cont.)

reader's quick reference and information and are not intended to supplant the information in Appendices B and C.

C. METHODOLOGY AND EVALUATION FORM

The next effort in Task II was to establish a methodology for the assessment of the component concepts. This was accomplished by preparing an evaluation form containing logic which led to the selection of components most likely to benefit from composite substitution.

Table IV shows an example of the "Task II Evaluation Form" for the oxidizer TPA on the LOX/LCH₄ engine. A detailed description of the parameters being evaluated in Table IV is found in Figure 28.

D. COMPONENT SELECTION

Each major component from the earth-to-orbit baseline engine (LOX/LCH₄, Cycle C) and the orbit-to-orbit baseline engine (O²V) underwent an evaluation in accordance with the methodology described in Table IV. Appendix D contains the evaluation forms for both engines. This evaluation narrowed the field of 92 major components to 12 components which could potentially benefit most from composite material substitution. The component selection rationale followed the steps shown below:

1. Ten parts were selected from each engine system solely on the basis of weight savings to be gained through composite substitution. (A total of 20 parts.)
2. The twenty parts were categorized and numbered based on percent of engine weight savings.

TABLE IV

TASK II EVALUATION FORM

ENGINE: LOX/CH₄ WEIGHT (lb): 895 RANKING: 1 TEMP (°F): -290 PRESSURE (PSI): 5262
 COMPONENT: LO₂ TPA % ENGINE WEIGHT: 17 1400

PART	MATERIAL DENSITY (lbs/in. ³)	CURRENT WEIGHT (lbs)	LENGTH/DIA (in.)	PROPOSED FAB METHOD	CRITICAL FAILURE MODE	PROPOSED MATERIAL	VOLUME FRACTION (%)
INDUCER HOUSING	.3	37	9.5/12.4	COMPRESSION MOLD, MACHINE	TENSION BENDING	HYBRID KEVLAR GRAPHITE EPOXY	100
INDUCER	.3	19	10.7/9.3	COMPRESSION MOLD OR REACTION INJECTION MOLD, MACHINE	TENSION HCF BENDING EROSION	GRAPHITE EPOXY	100
IMPELLER	.3	12	5/16.8	COMPRESSION MOLD OR REACTION INJECTION MOLD, MACHINE	TENSION HCF BENDING EROSION	GRAPHITE EPOXY	100
IMPELLER HOUSING	.3	475	15/24	AUTOCCLAVE MOLD	TENSION BENDING	HYBRID KEVLAR GRAPHITE EPOXY	100

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TABLE IV (cont.)

Page 2 of 2

NEW WEIGHT (lbs)	DELTA WEIGHT (lbs)	COST RATING	MAINTENANCE RATING	SELECTED/ EXCLUDED	JUSTIFICATION FOR EXCLUSION
16.2	-21	4.7	3.4	EXCLUDED	ANOTHER TPA HOUSING WAS SELECTED FOR DESIGN ANALYSIS
9.5	-10	4.9	3.4	EXCLUDED	NOT A MAJOR WEIGHT SAVING
6	-6	4.8	3.4	EXCLUDED	NOT A MAJOR WEIGHT SAVING
291	-184	3.4	3.5	SELECTED	

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Engine:	Either LOX/LH ₂ OTV or LOX/LCH ₄ Cycle C
Component:	Name of major component (i.e., turbopump)
Weight:	Baseline metallic weight of component
% Engine Weight:	Component weight/total engine weight
Ranking:	Each component is ranked according to percent of engine weight. The heaviest is ranked No. 1.
Temperature and Pressure:	Design conditions that the component experiences.
Part:	Subcomponent (i.e., shaft or rotor of the turbopump)
Material Density:	Current metallic density
Current Weight:	Subcomponent metallic weight (Estimated by obtaining the approximate volume of the subcomponent and multiplying it by the metallic density).
Length/Diameter:	Subcomponent envelope
Proposed Fabrication Method:	A fabrication process will be selected for the composite component on the basis of cost, quality level, and functional properties.
Critical Failure Mode:	Most likely mode of failure, determined by preliminary structural analysis. This assessment aids in the preliminary composite material selection.
Proposed Material:	A composite material will be selected as a substitute for the metallic part on the basis of the following: (1) propellant compatibility, (2) low temperature toughness, (3) elevated temperature and pressure stability and strength, and (4) storage deterioration characteristics. An extensive material properties literature search, in conjunction with consultation of material engineering specialists, will provide the information necessary to make these selections.
Volume Fraction:	Estimated percentage of the subcomponent which can be replaced with a composite material.
New Weight:	Obtained by multiplying the metallic volume by the composite density. The volume estimate will be refined in Task III if the structural analysis indicates any wall thickness changes.
ΔWeight:	Difference in weight between the baseline metallic part and its composite substitute.

Figure 28. Detailed Description of Task II Evaluation Form (Sheet 1 of 5)

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Cost:

The cost factor assessment methodology is illustrated on Sheet 3 of this figure. It provides a relative cost comparison for rocket engine components made from composite materials. Manufacturing costs are broken down into four categories: materials, labor, facilities and tooling. Material cost data are obtained from material suppliers. Labor manhours are estimated on the basis of the part's complexity and the required fabrication process. Tooling costs are similarly estimated. Facility costs are determined by the process selected and are estimated only on a very general basis.

The tooling, material, and labor costs are weighted equally because these manufacturing expenses are totally recovered in the price of the part. The facility cost is assigned a weighted factor one fifth (1/5) that of other component costs as these are prorated over other products produced at the facility.

Industrial engineering man-hour data available in the Air Force Composite Materials Design Guide (Manufacturing, Volume III) are being evaluated for use in estimating manufacturing costs (labor and tooling). Proposed manufacturing flow sheets, vendors, and subcontractors are also being used as sources of manufacturing cost data.

Maintainability:

The maintainability assessment methodology is illustrated on Sheet 4 of this figure. It provides a relative maintainability comparison for rocket engine components made from composite materials.

The maintainability factor is broken down into three categories: life, frequency of repair, and cost of repair. The life of a particular component is estimated from the stability of the material in the operational environments and/or its low cycle fatigue properties. The frequency of repair is estimated from the wear on the component due to chemical or mechanical erosion (abrasion) and/or its high cycle fatigue properties. The cost of repair is estimated from the amount of refurbishment required to restore the part to an acceptable level of performance.

A weighting factor of one fourth (1/4) was used to assess the effects of the frequency of repair and the cost of repair maintainability factors. The life component of maintainability was weighted higher (1/2) than the other components because it directly determines any need for maintenance.

Figure 28. Detailed Description of Task II Evaluation Form (Sheet 2 of 5)

MAINTAINABILITY ASSESSMENT

Item	$\frac{\sum \text{Maintainability Component (1-5)} \times \text{Weighting Factor (0-1)}}{\text{Life (1)}}$	$\frac{\text{Cost of Repair (3)}}{\text{Frequency of Repair (2)}}$	=	$\frac{\text{Rating (R)}}{\text{R}}$
LOX Pump				
Housing	MC x 1/2 +	MC x 1/4 +	=	R ¹
Shaft	MC x 1/2 +	MC x 1/4 +	=	R ²

Notes

- (1) Life Maintainability Factor Scale: 5 = Exceeds SOW Requirement
1 = Not Reusable
- (2) Frequency of Repair Factor Scale: 5 = No Incidence of Repairable Damage
1 = Refurbishment Required for Reuse (For Each Cycle)
- (3) Cost of Repair: 5 = Repair is Less than $\frac{\text{Replacement Cost}}{\text{Cycle Life}}$
1 = Repair Exceeds Replacement Cost

Figure 28. Detailed Description of Task II Evaluation Form (Sheet 4 of 5)

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Selected/Excluded:

All of the above-mentioned parameters will be evaluated for an acceptance-exclusion decision. Weight will be given major consideration in this decision, with cost, maintainability, performance, and life being considered secondarily.

Justification for Exclusion:

This will consist of a brief explanation why a subcomponent did not meet the requirements for composite substitution.

Figure 28. Detailed Description of Task II Evaluation Form (Sheet 5 of 5)

IV. D. Component Selection (cont.)

3. Any parts which duplicated the technology needs of another part were eliminated from consideration (retaining the one with the highest percent of engine weight savings.)
4. Finally, the number of parts was narrowed based on cost, life, and maintainability.

Table V shows a list of the twelve selected components, along with information on weight savings, proposed composite material, and proposed fabrication method. It must be stressed that these twelve components were selected primarily on the basis of weight savings and secondarily on the basis of cost, maintainability, performance, etc. It should also be understood that the numbers in the "Change in Weight" (ΔW) column in Table V were based solely on preliminary structural analysis at this point in time. These numbers, however, were considered sufficiently accurate to select the best "weight savers." A more precise ΔW number was obtained by measuring the cross-sectional area of the twelve finished drawings during Task III.

TABLE V

TASK II SELECTED COMPONENTS

ENGINE	% ENGINE WT SAVINGS	COMPONENT	PART	PROPOSED MATERIAL	PROPOSED FAB METH	Δ WT	COST	MAINT
1) OTV	3.9	NOZZLE DEPLOY SYSTEM	SHAFTS	GRAPHITE EPOXY	PULTRUSSION	-22.5	4.9	3.8
2) LOX/CH ₄	3.6	LOX TPA	IMPELLER HOUSING	GRAPHITE EPOXY	AUTOCLAVE MOLD	-184	4.8	3.5
3) OTV	3.2	VALVES AND ACTUATORS	VALVE BODIES	KEVLAR EPOXY	COMPRESSION MOLD	-18.2	4.8	2.8
4) LOX/CH ₄	2.8	CH ₄ TPA	IMPELLER HOUSING	GRAPHITE EPOXY	AUTOCLAVE MOLD	-140	3.8	3.9
5) OTV	2.3	NOZZLE DEPLOY SYSTEM	SUPPORT RING	GRAPHITE EPOXY	AUTOCLAVE MOLD	-13.5	4.7	5.0
6) OTV	2.3	VALVES AND ACTUATORS	SHAFTS, GEARS	FIBERGLASS POLYIMIDE	COMPRESSION MOLD	-12.8	4.8	3.6

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TABLE V (cont.)

ENGINE	% ENGINE WT SAVINGS	COMPONENT	PART	PROPOSED MATERIAL	PROPOSED FAB METH	Δ WT	COST	MAINT
7) LOX/CH ₄	2.3	INJECTOR	HOUSING	KEVLAR EPOXY	COMPRESSION MOLD	-119	4.1	3.7
8) OTV	2.3	COMBUSTION CHAMBER	SUPPORT STRUCTURE	KEVLAR GRAPHITE EPOXY	AUTOCLAVE MOLD	-13.2	4.5	5.0
9) LOX/CH ₄	2.1	LOX BOOST PUMP	HOUSING	KEVLAR GRAPHITE EPOXY	AUTOCLAVE MOLD	-106.7	4.3	3.2
10) LOX/CH ₄	1.3	NOZZLE	JACKET	GRAPHITE EPOXY	AUTOCLAVE MOLD	-63.8	4.5	3.9
11) LOX/CH ₄	1.2	GIMBAL	SEAT	GRAPHITE EPOXY	COMPRESSION MOLD	-62.8	4.6	4.5
12) LOX/CH ₄	1.1	COMBUSTION CHAMBER	MANIFOLDS	KEVLAR EPOXY	COMPRESSION MOLD	-54.8	4.1	3.7

V. TASK III - CONCEPTUAL DESIGN ASSESSMENT

A. OBJECTIVES

The major objectives of Task III were to prepare conceptual design drawings (cross sections) of each of the twelve components selected in Task II and to perform appropriate structural analyses as required to obtain realistic weight estimates. A secondary objective was to visit outside vendors in order to supplement our knowledge of cost, life, fabrication, and maintainability.

B. STRESS ANALYSIS

Preliminary drawings of the twelve selected concepts were reviewed by both structural and material engineering specialists, and the following analysis steps were taken with respect to each drawing:

1. On- and off-axis material structural property calculations
2. Von Mises failure criteria for biaxial mechanical stability
3. Residual thermal stress calculations for interlaminar and coating-interfacial stability at cryogenic temperatures
4. Stress analysis calculations to determine minimum section requirements

C. FINAL DRAWINGS AND WEIGHT ESTIMATES

Subsequent to the structural analysis, the final cross-sectional drawings were prepared for each of the twelve selected components. These drawings, shown in Figures 29 through 40, contain fabrication notes and information on technology needs.

Technical drawing of a mechanical assembly, likely a pump or motor, showing a cross-section and a side view. The drawing includes dimensions and a title block.

Dimensions:

- Overall height: 34.00
- Base width: 9.00
- Base depth: 10.00

Section Labels:

- A-A
- B-B
- C-C
- D-D
- E-E
- F-F
- G-G
- H-H
- I-I
- J-J
- K-K
- L-L
- M-M
- N-N
- O-O
- P-P
- Q-Q
- R-R
- S-S
- T-T
- U-U
- V-V
- W-W
- X-X
- Y-Y
- Z-Z

Section A-A:

- 1. 1/2" DIA. HOLE
- 2. 1/4" DIA. HOLE
- 3. 1/8" DIA. HOLE
- 4. 1/16" DIA. HOLE
- 5. 1/32" DIA. HOLE
- 6. 1/64" DIA. HOLE
- 7. 1/128" DIA. HOLE
- 8. 1/256" DIA. HOLE
- 9. 1/512" DIA. HOLE
- 10. 1/1024" DIA. HOLE
- 11. 1/2048" DIA. HOLE
- 12. 1/4096" DIA. HOLE
- 13. 1/8192" DIA. HOLE
- 14. 1/16384" DIA. HOLE
- 15. 1/32768" DIA. HOLE
- 16. 1/65536" DIA. HOLE
- 17. 1/131072" DIA. HOLE
- 18. 1/262144" DIA. HOLE
- 19. 1/524288" DIA. HOLE
- 20. 1/1048576" DIA. HOLE
- 21. 1/2097152" DIA. HOLE
- 22. 1/4194304" DIA. HOLE
- 23. 1/8388608" DIA. HOLE
- 24. 1/16777216" DIA. HOLE
- 25. 1/33554432" DIA. HOLE
- 26. 1/67108864" DIA. HOLE
- 27. 1/134217728" DIA. HOLE
- 28. 1/268435456" DIA. HOLE
- 29. 1/536870912" DIA. HOLE
- 30. 1/1073741824" DIA. HOLE
- 31. 1/2147483648" DIA. HOLE
- 32. 1/4294967296" DIA. HOLE
- 33. 1/8589934592" DIA. HOLE
- 34. 1/17179869184" DIA. HOLE
- 35. 1/34359738368" DIA. HOLE
- 36. 1/68719476736" DIA. HOLE
- 37. 1/137438953472" DIA. HOLE
- 38. 1/274877906944" DIA. HOLE
- 39. 1/549755813888" DIA. HOLE
- 40. 1/1099511627776" DIA. HOLE
- 41. 1/2199023255552" DIA. HOLE
- 42. 1/4398046511104" DIA. HOLE
- 43. 1/8796093022208" DIA. HOLE
- 44. 1/17592186044416" DIA. HOLE
- 45. 1/35184372088832" DIA. HOLE
- 46. 1/70368744177664" DIA. HOLE
- 47. 1/140737488355328" DIA. HOLE
- 48. 1/281474976710656" DIA. HOLE
- 49. 1/562949953421312" DIA. HOLE
- 50. 1/1125899906842624" DIA. HOLE
- 51. 1/2251799813685248" DIA. HOLE
- 52. 1/4503599627370496" DIA. HOLE
- 53. 1/9007199254740992" DIA. HOLE
- 54. 1/18014398509481984" DIA. HOLE
- 55. 1/36028797018963968" DIA. HOLE
- 56. 1/72057594037927936" DIA. HOLE
- 57. 1/144115188075855872" DIA. HOLE
- 58. 1/288230376151711744" DIA. HOLE
- 59. 1/576460752303423488" DIA. HOLE
- 60. 1/1152921504606846976" DIA. HOLE
- 61. 1/2305843009213693952" DIA. HOLE
- 62. 1/4611686018427387904" DIA. HOLE
- 63. 1/9223372036854775808" DIA. HOLE
- 64. 1/18446744073709551616" DIA. HOLE
- 65. 1/36893488147419103232" DIA. HOLE
- 66. 1/73786976294838206464" DIA. HOLE
- 67. 1/147573952589676412928" DIA. HOLE
- 68. 1/295147905179352825856" DIA. HOLE
- 69. 1/590295810358705651712" DIA. HOLE
- 70. 1/1180591620717411303424" DIA. HOLE
- 71. 1/2361183241434822606848" DIA. HOLE
- 72. 1/4722366482869645213696" DIA. HOLE
- 73. 1/9444732965739290427392" DIA. HOLE
- 74. 1/18889465931478580854784" DIA. HOLE
- 75. 1/37778931862957161709568" DIA. HOLE
- 76. 1/75557863725914323419136" DIA. HOLE
- 77. 1/151115727451828646838272" DIA. HOLE
- 78. 1/302231454903657293676544" DIA. HOLE
- 79. 1/604462909807314587353088" DIA. HOLE
- 80. 1/1208925819614629174706176" DIA. HOLE
- 81. 1/2417851639229258349412352" DIA. HOLE
- 82. 1/4835703278458516698824704" DIA. HOLE
- 83. 1/9671406556917033397649408" DIA. HOLE
- 84. 1/19342813113834066795298816" DIA. HOLE
- 85. 1/38685626227668133590597632" DIA. HOLE
- 86. 1/77371252455336267181195264" DIA. HOLE
- 87. 1/154742504910672534362390528" DIA. HOLE
- 88. 1/309485009821345068724781056" DIA. HOLE
- 89. 1/618970019642690137449562112" DIA. HOLE
- 90. 1/1237940039285380274899124224" DIA. HOLE
- 91. 1/2475880078570760549798248448" DIA. HOLE
- 92. 1/4951760157141521099596496896" DIA. HOLE
- 93. 1/9903520314283042199192993792" DIA. HOLE
- 94. 1/19807040628566084398385987584" DIA. HOLE
- 95. 1/39614081257132168796771975168" DIA. HOLE
- 96. 1/79228162514264337593543950336" DIA. HOLE
- 97. 1/158456325028528675187087900672" DIA. HOLE
- 98. 1/316912650057057350374175801344" DIA. HOLE
- 99. 1/633825300114114700748351602688" DIA. HOLE
- 100. 1/1267650600228229401496703205376" DIA. HOLE
- 101. 1/2535301200456458802993406410752" DIA. HOLE
- 102. 1/5070602400912917605986812821504" DIA. HOLE
- 103. 1/10141204801825835211973625643008" DIA. HOLE
- 104. 1/20282409603651670423947251286016" DIA. HOLE
- 105. 1/40564819207303340847894502572032" DIA. HOLE
- 106. 1/81129638414606681695789005144064" DIA. HOLE
- 107. 1/162259276829213363391578010288128" DIA. HOLE
- 108. 1/324518553658426726783156020576256" DIA. HOLE
- 109. 1/649037107316853453566312041152512" DIA. HOLE

Figure 29. LCH₄ High-Speed TPA (ALRC Drawing No. 1196001)

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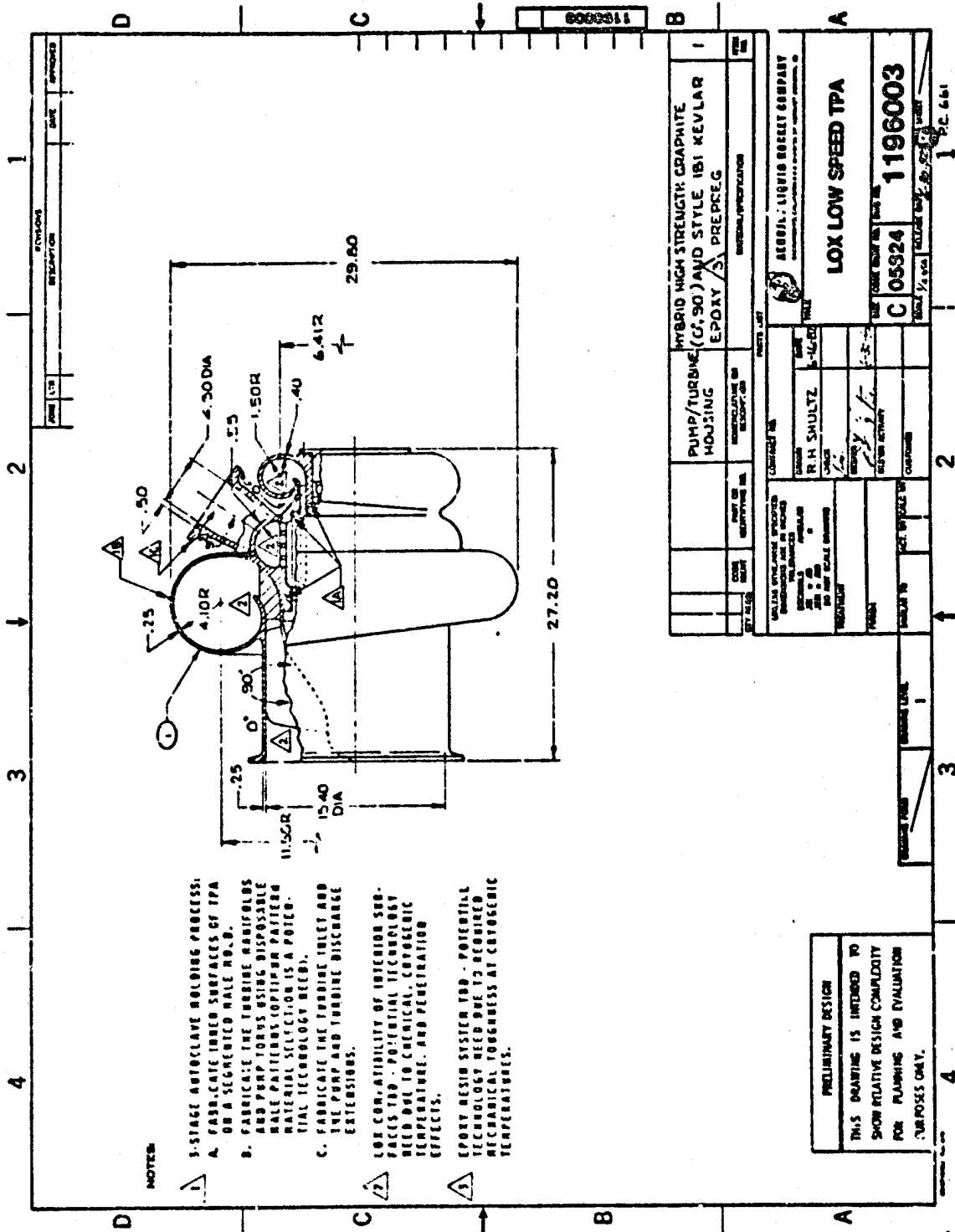


Figure 31. LOX Low-Speed TPA (ALRC Drawing No. 1196003)

Technical Drawing: SCAT-CRIBAL BEARING

Part Number: D 05374 1196005

Section: SECTION 1196005 BEARING (SCAT-CRIBAL BEARING)

Material: ALUMINUM

Dimensions:

- Overall Length: 1.00
- Overall Width: 1.00
- Overall Height: 1.00
- Inner Diameter: 0.50
- Outer Diameter: 0.75
- Thickness: 0.125

Notes:

1. ALL DIMENSIONS ARE IN INCHES.
2. TOLERANCES ARE AS SHOWN.
3. SURFACES ARE TO BE FINISHED.
4. MATERIAL IS TO BE ALUMINUM.
5. PARTS ARE TO BE IDENTIFIED BY PART NUMBER.

Part List:

Part Number	Description	Quantity
D 05374 1196005	SCAT-CRIBAL BEARING	1

Figure 33. Seat - Gimbal Bearing (ALRC Drawing No. 1196005)

NOTES:

- FABRICATION STEPS:
 - AUTOCCLAVE HOLD (1) AND (2) SEPARATELY.
 - AUTOCCLAVE HOLD "INJECTOR MANIFOLD" TO (1).
 - ADHESIVELY BOND (1) TO (2).

119600

INJECTOR HOUSING

C05824 1196007

PRELIMINARY DESIGN

THIS DRAWING IS INTENDED TO SHOW RELATIVE DESIGN COMPLEXITY FOR PLANNING AND EVALUATION PURPOSES ONLY.

REVISIONS

REV	DATE	DESCRIPTION
1	11/11/60	INITIAL DESIGN
2	11/11/60	STILL NEED 2 REV
3	11/11/60	PREPARED

DESIGNED BY D. M. SMULTZ
CHECKED BY J. M. SMULTZ
DATE 11/11/60
SCALE 1:1
PROJECT 119600
DRAWING NO. C05824
REV 1
DATE 11/11/60
DESCRIPTION INITIAL DESIGN

一

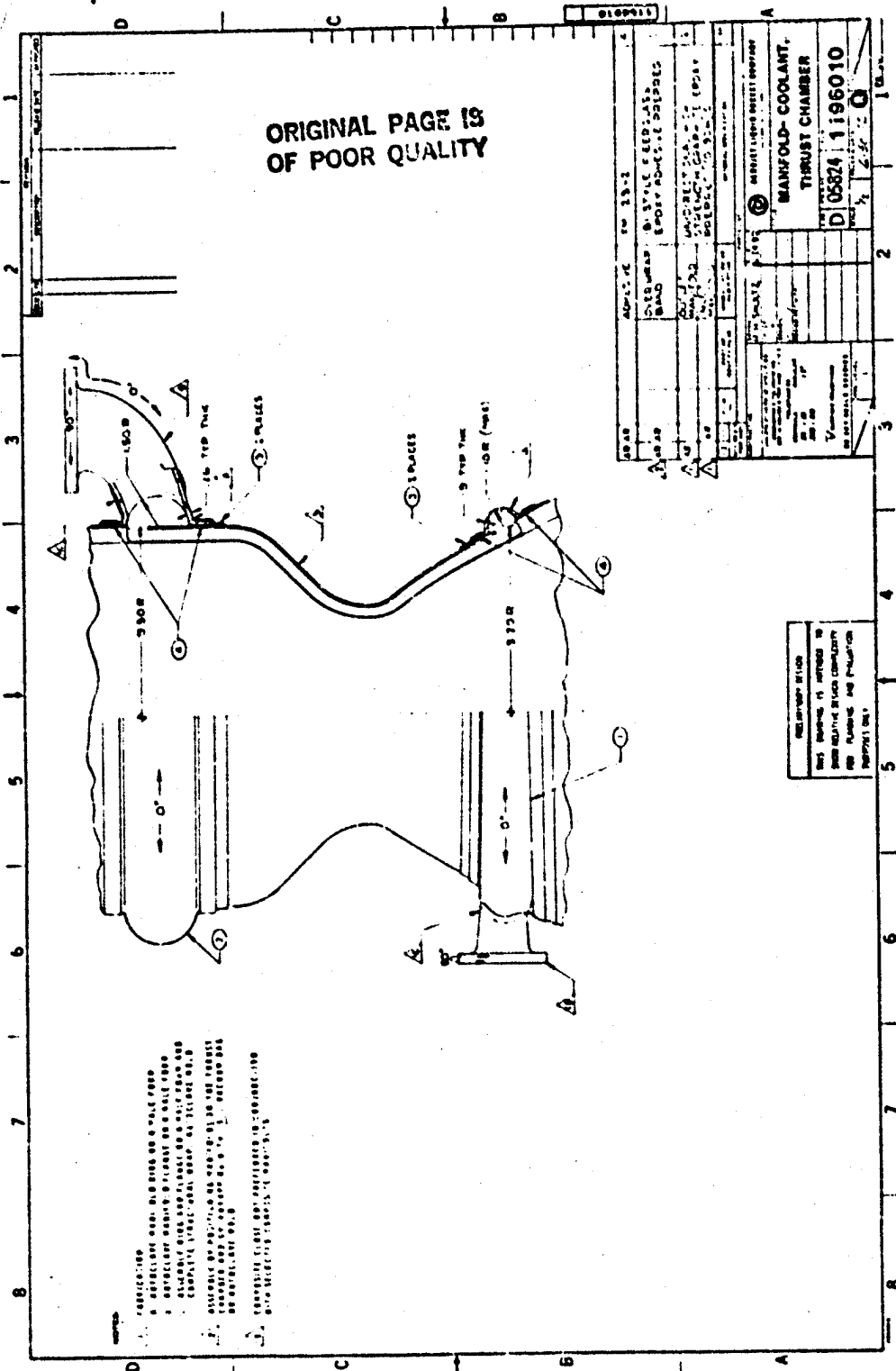


Figure 38. Manifold - Coolant, Thrust Chamber (ALRC Drawing No. 1196010)

Figure 40. Gear - Actuator, Valve (ALRC Drawing No. 1196012)

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V. C. Final Drawings and Weight Estimates (cont.)

The weights of the composite-substituted components were then determined by using Simpson's rule to calculate part volume from the final drawing dimensions. Table VI contains data on component metallic weight, corresponding composite weight, and the percent weight savings achieved through composite substitution.

D. OUTSIDE VENDOR DESIGN INPUT CONCERNING REINFORCED PLASTIC COMPOSITES

The design concepts for the twelve selected parts benefited from consultation with a great variety of expert sources outside of ALRC during the course of the program. Table VII contains a complete list of every company contacted for consultation purposes.

A meeting was held with nonmetallic composite experts from the Aerojet Strategic Propulsion Company (ASPC) to review the twelve cross-sectional drawings from Task III. Their major comments were as follows:

- 1) Some of the more complex shapes would be a challenge from a fabrication standpoint, but are all considered feasible.
- 2) Extensive use of chopped molding compound (isotropic material) in low stress areas would promote the producibility of thick sections and complex surfaces where maintaining fiber alignment is difficult.
- 3) The use of woven fiber in low stress areas instead of uni-directional prepreg would aid in controlling fiber alignment.

TABLE VI

COMPONENT METALLIC WEIGHT VERSUS COMPOSITE WEIGHT

	Impeller Housing CH ₄ High-Speed TPA	Impeller Housing LOX High-Speed TPA	Boost Pump Housing LOX Low-Speed TPA	OTV Throat Support Structure	Gimbal Seat	OTV Nozzle Extension Shafts	Injector Housing	OTV Skirt Support Ring	Nozzle Jacket	Combustion Chamber Manifolds	OTV Valve Housing	Valve Gear
	<u>1196001</u>	<u>1196002</u>	<u>1196003</u>	<u>1196004</u>	<u>1196005</u>	<u>1196006</u>	<u>1196007</u>	<u>1196008</u>	<u>1196009</u>	<u>1196010</u>	<u>1196011</u>	<u>1196012</u>
Metallic Weight (lb)	163	144	193	22	29	24	51	27	55	50	10	21
Composite Weight (lb)	34	49	97	5.6	13	4.9	24	14	11	11	2.6	4.6
% Weight Savings	79	66	50	75	55	80	53	48	80	78	74	78
Rank	3	8	11	6	9	1	10	12	1	4	7	4

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TABLE VII

OUTSIDE VENDORS CONSULTED

<u>VENDORS</u>	<u>SPECIALTY</u>
1. AERJET SOLID PROPUSSION COMPANY	CARBON-CARBON AND FILAMENT WINDING
2. AFTON PLASTICS MOLDING COMPANY	PCTFE BARRIER COATINGS
3. AMERICAN AUTOMATED ENGINEERING INC.	AUTOCCLAVE COMPRESSION AND TRANSFER MOLDING
4. CENTURY PLASTICS, INC.	VACUUM BAG MOLDING
5. DVA COMPOSITE SPECIALTIES, INC.	METAL MATRIX COMPOSITES MANUFACTURING
6. EDLER INDUSTRIES, INC.	AUTOCCLAVE MOLDING
7. FIBRO, INCORPORATED	HARD AND CHOPPED-FIBER SPRAY LAY-UP
8. FIBERITE	COMPOSITE MATERIALS SUPPLIER
9. HAVIG-REINHOLD, INC.	AUTOCCLAVE AND COMPRESSION MOLDING
10. HITCO	AUTOCCLAVE MOLDING AND TAPE WRAPPING
11. M.C. GILL CORPORATION	BRAIDING
12. METCO	METAL MATRIX COMPOSITES TESTING
13. PETERSON PRODUCTS	TRANSFER MOLDING
14. POLYMER DESIGN	RESIN CASTING
15. POLY-TRUSSIONS, INC.	PULTRUSSION
16. REYNOLDS AND TAYLOR	AUTOCCLAVE MOLDING AND FILAMENT WINDING
17. RISDON CORPORATION	VACUUM DEPOSITED METALLIC COATINGS
18. SHIPLEY COMPANY, INC.	ELECTROLESS NICKEL COATING
19. SWEDOW, INC.	COMPRESSION MOLDING
20. 3M	COMPOSITE MATERIALS SUPPLIER

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V. D. Outside Vendor Design Input Concerning Reinforced Plastic Composites (cont.)

These comments were incorporated into the design of the components which were recommended for fabrication in Task V of this program.

In addition to the ASPC consultation, a trip was made to Los Angeles to meet with six fabricators of reinforced plastic composite materials. Appendix E lists the persons contacted during the visits, along with the product lines of the companies. Seven of the completed Task III drawings were reviewed by each of the contractors, and they were asked to assess their capabilities to make the parts together, listing the anticipated processing difficulties. They made comments on minor part-geometry redesign which would simplify fabrication and also indicated that they would like to be involved in the design of any part which would ultimately be fabricated at their facility. We also feel that if the bigger companies with composite design experience were involved in the design from the beginning, a lot of unnecessary and expensive supporting technology testing could be avoided in any follow-on fabrication program. All of the companies felt that the components would be satisfactory for manufacturing, and some of the companies prepared price quotes for inclusion in the Task V section of this report.

E. OUTSIDE VENDOR DESIGN INPUT CONCERNING METAL MATRIX COMPOSITES

Outside vendor consultations (Table VII) were made during the course of the program with regard to the application of metal matrix composites to the selected components. The companies visited were Nevada Engineering & Technology Corporation (NETCO), DWA Composite Specialities, and Aerojet Solid Propulsion Company. A summary of their major comments is presented in the following listing. (Also see Appendix E.)

V. D, Outside Vendor Design Input Concerning Reinforced Plastic Composites (cont.)

- 1) Selected parts too complex for fabrication by laying up MMC laminates and diffusion bonding.
- 2) TPA impeller housing is well beyond state of the art.
- 3) In complex shapes with multidirectional stress distributions, boron-aluminum and graphite aluminum become inefficient.
- 4) Valve housing could be fabricated from an aluminum-silicon carbide composite (powder metallurgy) such as DWA-AL. This material, however, possesses poor weldability.
- 5) MMC components would be lighter than those made from unreinforced metal but heavier than those made from RPC's.
- 6) No problems with permeability or compatibility.

Based on the recommendations of both outside expert sources and ALRC materials engineering experts, it was decided that reinforced plastic composites were preferable for fabricating the selected designs (Task V). Metal matrix composites are out of consideration at the present time because of their higher cost, lower specific strength, and greater fabrication difficulties. Table VIII contrasts the weights and fabrication risks of three individual components made from 1) RPC, 2) boron-aluminum, 3) silicon carbide-aluminum, and 4) baseline metal, respectively. The weights in Table VIII were determined analytically by performing a stress analysis to determine the appropriate wall thickness for each material. It can be seen that the RPC components are lighter in every case and pose far fewer fabrication difficulties.

If higher temperatures and greater performance become more important "drivers" than weight savings in future programs, it is possible that the use of certain MMC or ceramic materials would be indicated. For the present study, however, it is clear that RPC components are lighter and more cost-effective.

TABLE VIII
PLASTIC MATRIX VERSUS METAL MATRIX COMPARISON CHART

Material	LCH ₄ TPA Discharge Housing - 1196001 Weight (lb) Fab. Risk	Injector Housing 1196007 Weight (lb) Fab. Risk	Valve Body 1196011 Weight (lb) Fab. Risk
Reinforced Plastic Composite	34 Low	24 Low	1.3 Low
Crossplied Boron- Aluminum Composite	68 High	31 High	2.1 High
Silicon Carbide- Aluminum Particulate Composite	75 High	38 High	2.4 Moderate
Baseline Metal	163 Low	51 Low	5.0 Low

VI. TASK IV - CRITICALITY RANKING OF TECHNOLOGY NEEDS

A. OBJECTIVES

The first objective of Task IV was to define the technology needs involved in developing the twelve selected concepts and to evaluate those needs in terms of level of risk involved in bringing those technologies to operational status. The second objective of Task IV was to provide a criticality ranking of the identified technology needs and to justify the rankings with narrative and figures of merit.

B. TECHNOLOGY NEEDS

At the commencement of Task IV, a great deal of thought was given to defining the technological barriers that would need to be overcome in order to successfully build production rocket components out of reinforced plastic composites. A list of these technology needs is shown in Table IX.

Each of these technology needs was evaluated to establish the impact of required technology. Figure 41 is a schematic which outlines the steps taken during this evaluation. Each major component was examined to identify any parts that had not been developed. Except for rocket nozzles, where composite nozzles have been used, essentially all composite-substituted components fall into the new-with-composite screening category.

Those parts requiring further development were then evaluated in terms of the level of risk that would be involved in bringing them to operational status. The degree of risk was categorized between low (for components that are just short of being operational) to high (for components that have only been proposed or theorized). The sensitivity of each component to these risks was assessed in terms of cost, schedule, performance, life, weight, and commonality of technology. The results of this evaluation were

TABLE IX
TECHNOLOGY NEEDS LISTING

- | | |
|------|------------------------------------|
| 1.0 | H ₂ Compatibility |
| 2.0 | O ₂ Compatibility |
| 3.0 | CH ₄ Compatibility |
| 4.0 | Low Temperature Toughness |
| 5.0 | Fabrication |
| 5.1 | Mechanical Fastening |
| 5.2 | Sealing Surface Finish |
| 5.3 | Vane Manufacturing Method |
| 5.4 | Vane Attachment Method |
| 5.5 | Fabrication Sequence |
| 5.6 | Barrier Coating Process |
| 5.7 | Plumbing Connections |
| 5.8 | Detail Joining Methods |
| 5.9 | Detail Fabrication Methods |
| 5.10 | Mold Design |
| 6.0 | Cryogenic Properties |
| 7.0 | Interface Properties |
| 8.0 | Metal Coating Interface Properties |
| 9.0 | Differential Expansion Properties |
| 10.0 | Solar Radiation Effects |
| 11.0 | Low Cycle (Thermal) Fatigue |
| 12.0 | High Cycle Fatigue (HCF) |
| 13.0 | Bearing Surface Lubricant |

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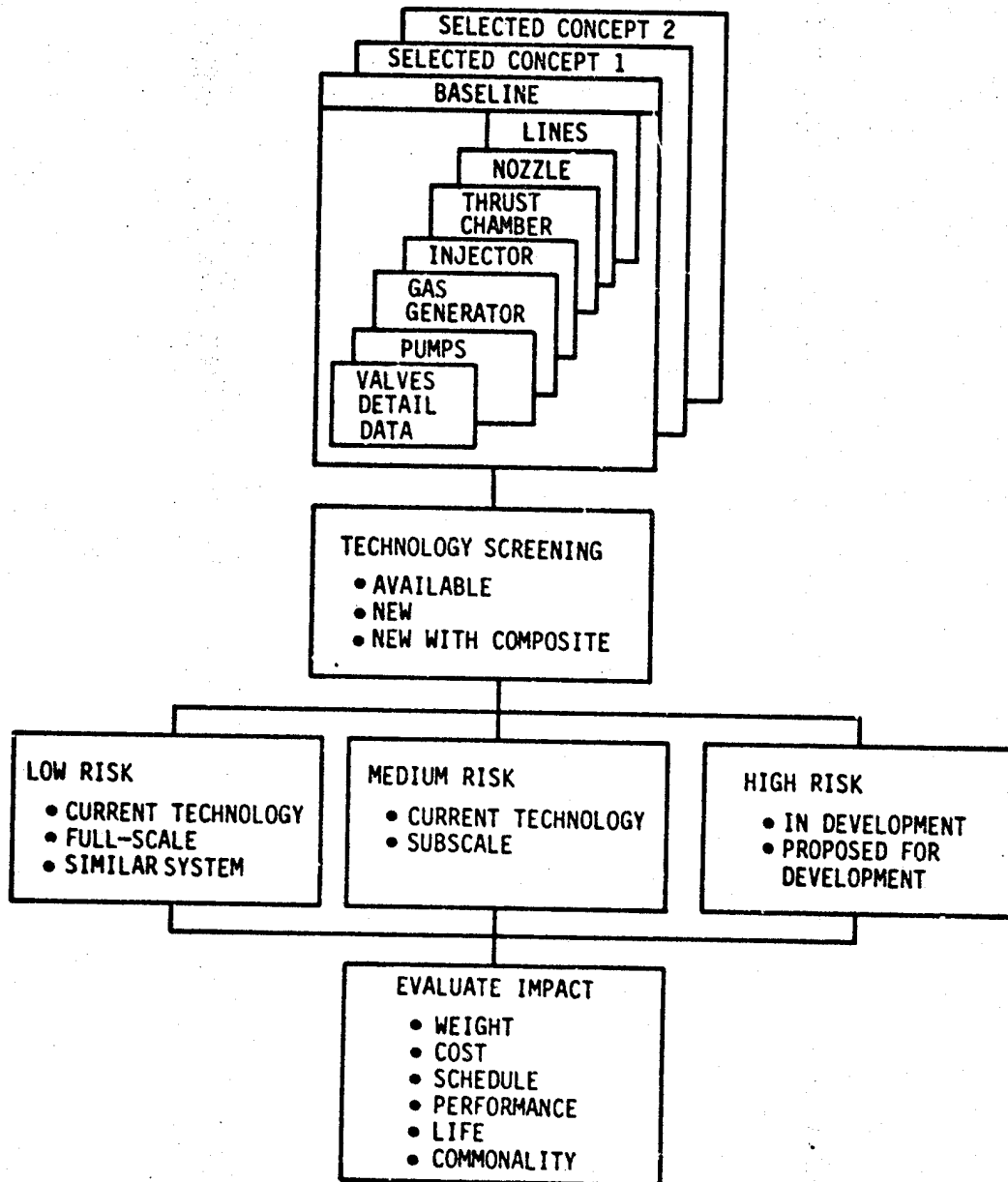


Figure 41. Technology Risk Assessment Procedure

VI. B. Technology Needs (cont.)

documented in a series of "Technology Need Definition" forms. One of these forms was filled out for each of the categories shown in Table IX. This form defined the technology need, assessed its risk, suggested an approach to the problem, and proposed a solution. An example of one of these forms is shown as Figure 42 (Barrier Coating Process), and the balance is included as Appendix F in this report.

Many of the thirteen technology needs lend themselves to easy solutions and were only included out of a desire for thoroughness (i.e., solar radiation, bearing surface lubricant, etc.). It is believed that the balance of the technology needs can be solved through straightforward laboratory and test programs. This optimism about the ability to quickly solve the thirteen technology needs through technology programs is based on the following rationale:

1.0-3.0 Propellant Compatibility - Problems which can result from chemical incompatibility or from freeze-thaw cycling (causing cracks) will be precluded by the application of internal barrier coatings. (See 8.0 below.)

4.0 Low Temperature Toughness - Thermoset polymer matrix composites are brittle materials at room temperature. Evidence of this is seen in the resin microcracking that results from the residual thermal stress from curing at elevated temperature. These composite materials, however, exhibit a remarkable toughness capability because of the many individual fiber and resin interfaces, each of which is structurally redundant. This results in a fracture process that is progressive rather than sudden, as is characteristic of conventional brittle materials. Such behavior is characteristic of outstanding fracture toughness. Because the strength of polymer matrix composites is known to increase slightly at cryogenic temperatures, their fracture

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ITEM: 5.6 - Barrier Coating Process				
DESCRIPTION: High-performance plastic composites must be sealed in order to contain liquids and vapors.				
ASSESSMENT OF RISK: <table><tr><td>High</td><td>*</td><td>Medium</td><td>Low</td></tr></table> *Microcracking occurs in the resin matrix of high-performance composite materials. These cracks result from residual and applied stresses. They render the resin matrix permeable to vapors and liquids.	High	*	Medium	Low
High	*	Medium	Low	
APPROACH: Several barrier coatings (metal foils, plastic films, etc.) have been used successfully to seal composite materials. These coating materials and processes will be evaluated to select the optimum system for a given rocket engine component.				
PROPOSED SOLUTION: Ductile barrier coatings are required to seal composite materials.				

Figure 42. Technology Need Definition, Barrier Coating Process

VI. B. Technology Needs (cont.)

toughness is not expected to decrease significantly at low temperatures because of any embrittling effects.

Structural element tests (including impact) at cryogenic temperatures are planned to confirm that this is true for the candidate composite materials and processes being considered for this program.

5.0 Fabrication - Any potential fabrication problems (i.e., fastening, barrier coating, sealing surface finish, etc.) will be solved through the development of manufacturing techniques during the technology programs. None of the identified fabrication technology needs pose a serious problem in view of the current state of the art with RPC's.

6.0 Cryogenic Properties - This is a low-risk technology need due to the existence of commercial composite materials which display high strength and good fracture toughness at cryogenic temperatures. Before finalizing any design, the structural and physical properties of the candidate material will be verified by structural testing at cryogenic temperatures.

7.0 Interface Properties - Strong adhesive bonds between two composite parts or between a composite and a metal part have been demonstrated successfully in the aircraft industry. The stability of these adhesive bonds at cryogenic temperatures will be analyzed, and each proposed combination will be tested to validate the predictions. In the event that the predicted structural performance is not attained because of poor adhesive bonding, other design alternatives will be investigated (i.e., bolting, riveting, sewing, etc.).

VI. B. Technology Needs (cont.)

8.0 Metal Coating Interface Properties - The use of metallic barrier coatings is anticipated in order to protect the composite material from degradation caused by contact with the liquid rocket propellants. The large temperature excursions caused by cryogenic conditions are expected to result in significant bondline strain. This strain problem can be partially mitigated by tailoring the thermal expansion properties of the composite through control reinforcement and fiber volume (Ref. 8). Another technique which has been successfully used is to apply an elastomeric adhesive tie coat that approximates the expansion characteristics of the metal barrier (Ref. 9). A stable metal coating interface should result if the adhesive bond to the composite is strong enough to prevent separation during thermal excursions. The use of more than one tie coat adhesive introduces additional interfaces and reduces the stress at the two key interfaces for greater bond stability.

Satisfactory metal-lined tanks and propellant (LOX) lines of polymer composite have been fabricated and tested by the Martin Company under contract to NASA (Ref. 10 and 11).

9.0 Differential Expansion Properties - Differential expansion between contacting dissimilar materials results in interfacial stress. Stress rupture and disbonding are two harmful effects of differential expansion. A preliminary structural analysis performed at ALRC indicated that satisfactory dissimilar material interfaces can be developed over the temperature ranges anticipated (see 8.0 above).

10.0 Solar Radiation Effects - The surface of epoxy matrix composite materials is degraded by solar radiation. This degradation results in surface crazing and decreases the composites' chemical resistance. This appears to be a low-risk technology need since protective coatings are

VI, B. Technology Needs (cont.)

available to block solar radiation. The effectiveness of these coatings can be demonstrated in ultraviolet (UV) weatherometer exposure tests.

11.0 Low Cycle Fatigue (LCF) - Low cycle (thermal) fatigue results from structural damage in which thermal stress was a contributing factor. In composite materials, these stresses can result because of flaws in the material, dissimilar material interfaces, anisotropy, or poor bonding. Past experience shows that once the cause of the structural damage has been identified (through structural element testing), one can design around it. Examples of composite components in use today which are designed to successfully withstand low cycle thermal fatigue are 1) fiberglass LN₂ bottles, 2) natural gas vessels, and 3) parts in cryogenic wind tunnels.

12.0 High Cycle Fatigue (HCF) - High cycle (thermal) fatigue results from structural damage that is caused by stress-induced microstructural changes in the material. These changes occur generally because of some discrete mechanism that allows the stress to reach a destructive level. This mechanism depends upon a crack, void, disbond, or dissimilar material interface and a dynamic change in the level of stress due to vibration or movement.

In the case of RPC's, designing for HCF is a low-risk technology need. Example of RPC's used in HCF applications abound (i.e., gears, machinery, compressor blades, etc.). This serves to underscore the fact that composites are lighter, stiffer, and more structurally efficient than their metallic counterparts.

13.0 Bearing Surface Lubricant - Polymer composite materials abrade more easily than metallic materials because of the resin micro-cracking. A lubricant can be helpful in sealing the surface and providing a smooth, low friction surface to reduce abrasion damage due to sliding and

VI. B. Technology Needs (cont.)

rubbing. It should be a simple task to select a commercial lubrication system compatible with composite materials, the liquid rocket engine environment, and the vacuum conditions of space.

C. CRITICALITY RANKING OF TECHNOLOGY NEEDS

Using the weight data from Table VI and the information from the "Technology Needs Definition" forms, a "Technology Needs Cross-Reference Chart" was formulated (see Table I). This chart displays the number of components common to each technology and shows the percentage of weight reduction associated with the application of each technology need. This allows the ranking of technology needs as well as specific components in terms of weight reduction payoffs. It also displays our assessment of the risk associated with overcoming each technology barrier.

Since Table I is basically a compendium of the studies conducted in Tasks I through IV, it was used as a guide in selecting the follow-on tasks recommended for Task V of this study. Those selected for fabrication in Task V represent the components which provide the greatest percentage of weight savings through composite substitution and which also encompass the solution to a wide variety of technology needs.

VII. TASK V - RECOMMENDED TASKS

A. OBJECTIVE

The purpose of Task V was to recommend a minimum of two follow-on tasks involving component fabrication and testing. It was desired that the selected components not only show promising weight savings with composite substitution but that their construction also encompass the solution to a wide variety of technology needs, thus paving the way for a large number of composite substitutions in the future.

Another objective of Task V was to formulate a schedule and budget for the analysis, design, fabrication, and testing of the selected components.

B. RECOMMENDATIONS

The recommended follow-on tasks were selected by using the critical technology need ranking developed in Task IV (see Table I). This ensured that a combination of weight reduction and technology advancement features were incorporated into a minimum-cost, low-risk program.

The components selected for fabrication and further study in a follow-on program are as shown below:

<u>PN</u>	<u>Component</u>	<u>% Weight Savings Rank</u>	<u>Number of Technology Needs Addressed</u>
1196011	OTV Valve Housing	8	14
1196001	LCH ₄ High-Speed TPA Impeller Housing	4	17
1196006	OTV Nozzle Extension Shafts	1	6
1196008	OTV Skirt Support Ring	5	4

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VII, B, Recommendations (cont.)

The OTV valve housing shows significant weight savings and requires the solution of fourteen technology needs. This component could be immediately useful on several engines while solving problems connected with many other components.

The LCH₄ high-speed impeller housing is the biggest weight saver on the 600K-lbf booster engine when made with composites. It also presents the most complications in terms of advancing the state of the art in composite fabrication technology. If this component could be successfully built, construction of any of the twelve components selected in Task III would be facilitated greatly.

The OTV extension shaft yields the greatest percentage of engine weight savings. At the same time, its fabrication process is fairly simple and would address the solution of only six technology needs. The extension shafts can be inserted directly into the OTV skirt support ring to form a subassembly. This support ring was also selected because it is simple to fabricate and shows a good weight savings.

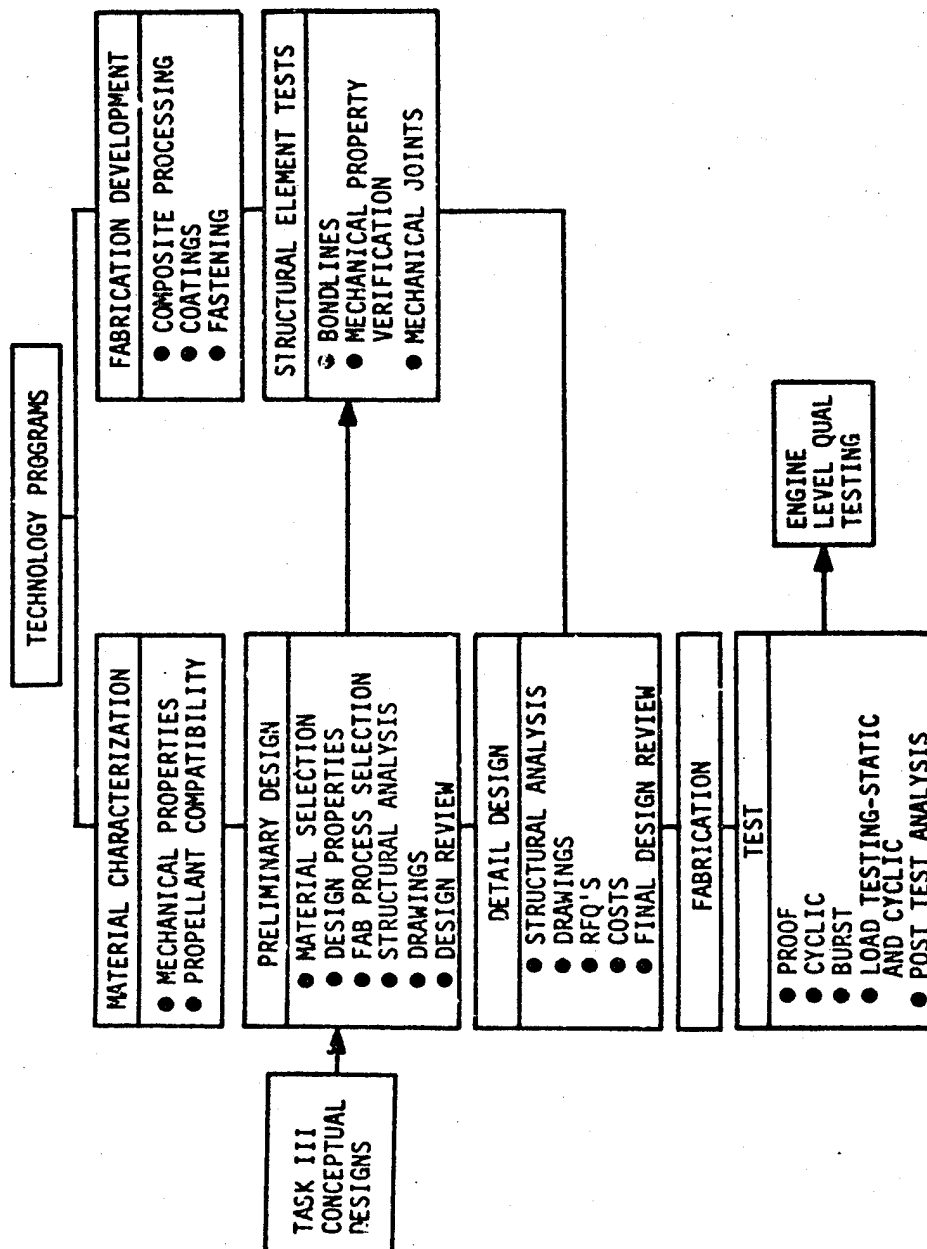
Notice should be taken that the four recommended tasks are not merely the four top weight savers based on the Task III weight analysis. They were selected not only to show good weight savings but also to cover the spectrum of technology needs from the simplest to the most complex. They may be fabricated either together or singly, depending on NASA's schedule and budgetary needs.

C. PROGRAM PLANS FOR THE SELECTED COMPONENTS

Table X shows a schematic representation of the general design and analysis steps that would be followed for any of the four recommended tasks.

TABLE X.

DESIGN AND ANALYSIS STEPS FOR RECOMMENDED PARTS



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VII, C. Program Plans for the Selected Components (cont.)

The proposed program for each recommended task consists of five elements: (1) technology programs addressing the technology needs identified for each selected part; (2) a preliminary design incorporating the results of the material characterization portion of the technology programs and the conceptual design from Task III; (3) a final design incorporating the results of the preliminary design and the fabrication development portion of the technology programs; (4) fabrication; and (5) testing and evaluation of the tested part.

Each recommended task is costed separately, with a breakdown by element to allow funding options for a follow-on activity.

Technology Programs

A general description of each technology need is given in Section VI,B of this report. These programs are concerned with (1) the determination of mechanical and physical properties of candidate materials, (2) the effect of propellant exposure on these properties, and (3) the development of fabrication techniques for application to the final design. The purpose of the programs is to minimize risk in the design by providing the data required for material selection, structural analysis, and the processing parameters required for fabrication of the part. Each program will be formulated to identify the candidate materials, test specimens, test procedures, special test equipment, and test parameters. The results of cryogenic mechanical tests will be evaluated for ductility and toughness values with respect to those at room temperature. Propellant compatibility tests results will be evaluated as to chemical reactions and the effect of static and cyclic exposure on mechanical properties.

VII. C. Program Plans for the Selected Components (cont.)

Preliminary Design

The conceptual designs of Task III will be the basis for the development of a preliminary design that also incorporates the results of the material characterization portion of the technology programs (i.e., final material selection and design allowable properties). The Task III structural analysis hand calculations for the conceptual design will be refined to determine new section sizes and detail design features such as laminate orientations and thicknesses, bond lines, and mechanical joints. The preliminary design drawings will be reviewed with NASA for their approval.

Structural elements, based on the preliminary design, will be fabricated and mechanically tested to verify design property selection and the structural analyses. Failure to verify the conceptual design through structural element testing would require an iteration of the structural element tests.

Detail Design

The detail design will incorporate the results of the preliminary design and the structural element testing. A final computerized finite element structural analysis will be conducted to refine section sizes, bond areas, and mechanical joint details. Detail part and assembly drawings will be presented at a final review with NASA.

The detailed designs will be submitted to ALRC manufacturing and to outside suppliers that provided quotes for the study to finalize costs.

VII. C. Program Plans for the Selected Components (cont.)

Fabrication

The selected fabricators will be monitored to assure conformance to drawing requirements and quality control procedures, including raw material inspection, process controls, and nondestructive inspection of fabricated parts.

Testing

The test plan for the completed part will be formulated to simulate the duty cycle. If the part requires pressure testing, it will be sealed by using the attachment method to the adjoining part as indicated in the component design. The part will be proof-tested prior to cyclic pressure-testing with the propellant. In the event of failure during cyclic testing, a destructive post-test failure analysis will be conducted in an effort to determine failure mode and to determine the degree of material degradation. If cyclic testing reaches full duration, the part will be visually and nondestructively inspected to determine material degradation. At this time, the part will either be destructively analyzed or burst-tested and destructively analyzed.

As each of the four recommended subcomponents is entirely different in function and fabrication complexity, it necessitates a separate budget, schedule, and test plan for each one. The paragraphs which follow describe a unique program plan for each of the recommended parts. These program plans consist of the following: 1) a conceptual drawing of the subcomponent, 2) a fabrication process flowchart, 3) a summary of the required technology and component testing, and 4) a detailed schedule and budget for each program plan.

VII, C, Program Plans for the Selected Components (cont.)

1. OTV Valve Housing

The OTV valve housing, shown in Figure 43, was selected both for its significant engine weight savings (1.3%) and because its fabrication would address a total of fourteen technology needs. It is also a component which could be immediately useful on existing engines.

Figure 44 shows that the valve body would be filament-wound from graphite epoxy and thereafter autoclave-molded. The valve bosses would then be compression-molded separately from Kevlar-epoxy prepreg. After machining openings in the valve body, the bosses would be adhesively attached via an autoclave bonding process. The internal barrier coating could be performed on the mandrel before filament-winding the body, or they could be deposited internally by a variety of methods (i.e., electro deposition, vacuum deposition, etc.) after the valve body is completed. The specific barrier coating method selected would depend on the results of prior fabrication technology programs.

Figure 45 contains a summary of the material and fabrication technology tests which would be performed prior to fabricating the subcomponent. These tests would include 1) laboratory coupon tests to determine mechanical, thermal, and propellant compatibility properties, 2) fabrication and material process trials, and 3) structural element testing. After developing the technology and fabricating a valve housing, the housing would be proof-tested, cyclic pressure-tested (in LOX, LH₂, and LCH₄), and destructively burst-tested in LOX.

The schedule and budget for performing the technology, design, fabrication, subcomponent testing, and evaluation of the valve body are shown in Figure 46. The entire program would take place in a 13-month

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Figure 43. ORV Valve Housing

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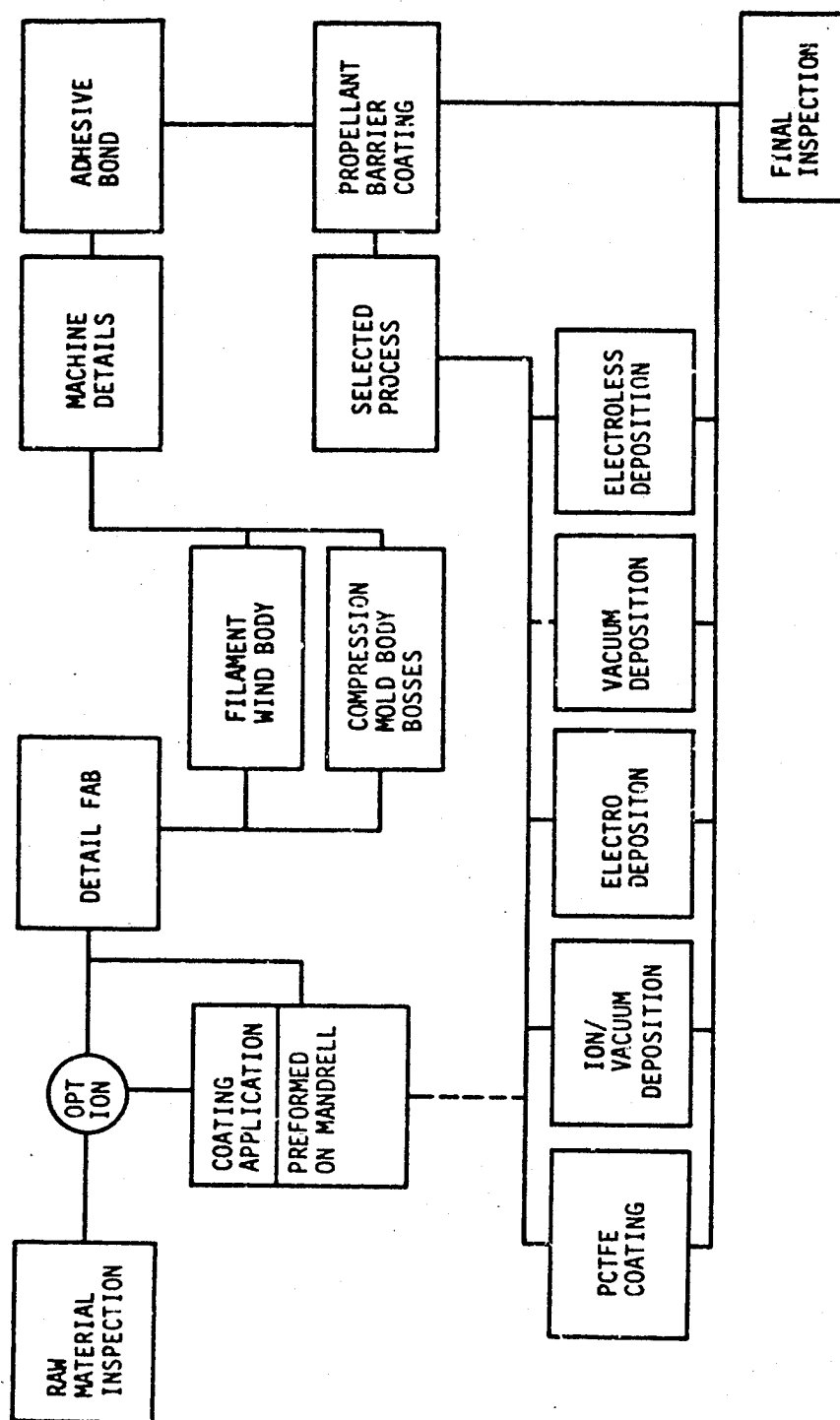


Figure 44. OTV Valve Housing Fabrication Process Flowchart

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- COUPON TESTS
 - PROPELLANT COMPATIBILITY [(LOX, LCH₄, LH₂) (IGNITION SENSITIVITY AND LONG-TERM DEGRADATION EFFECTS)]
 - LOW TEMPERATURE TOUGHNESS [(STATIC AND CYCLIC FLEXURAL TESTS) (FLAWED AND UNFLAWED SPECIMENS)]
 - BARRIER COATINGS [(FLEXURAL TESTS FOLLOWING PROPELLANT EXPOSURE) (ADHESION TEST AT CRYOGENIC TEMPERATURE)]
 - THERMAL EXPANSION PROPERTIES [(SUBSTRATE AND COATING MATERIALS AT CRYOGENIC TEMPERATURE) (ANISOTROPY DATA)]
 - STRUCTURAL PROPERTIES [(SUBSTRATE AND COATING MATERIALS AT CRYOGENIC TEMPERATURE) (ANISOTROPY DATA)]
- STRUCTURAL ELEMENT TESTS
 - FABRICATION AND MATERIAL PROCESS TRIALS (BARRIER COATING PROCESS, SEALING SURFACE FINISHING, DETAIL LAB METHODS, MACHINING, WELD DESIGN, JOINING, PLUMBING CONNECTIONS)
 - LOW CYCLE (THERMAL) FATIGUE
 - COATING PROCESS OPTIMIZATION (BONDING AIDS AND COATING THICKNESS)
 - KEY INTERFACE SHEAR TESTS IN LH₂
 - CYCLIC PRESSURE AND BURST TESTS
- COMPONENTS TESTS
 - PROOF
 - CYCLIC PRESSURE TESTS (LOX, LCH₄, LH₂)
 - BURST TEST IN LOX

Figure 45. 1196011 Valve Housing Technology Program and Component Testing

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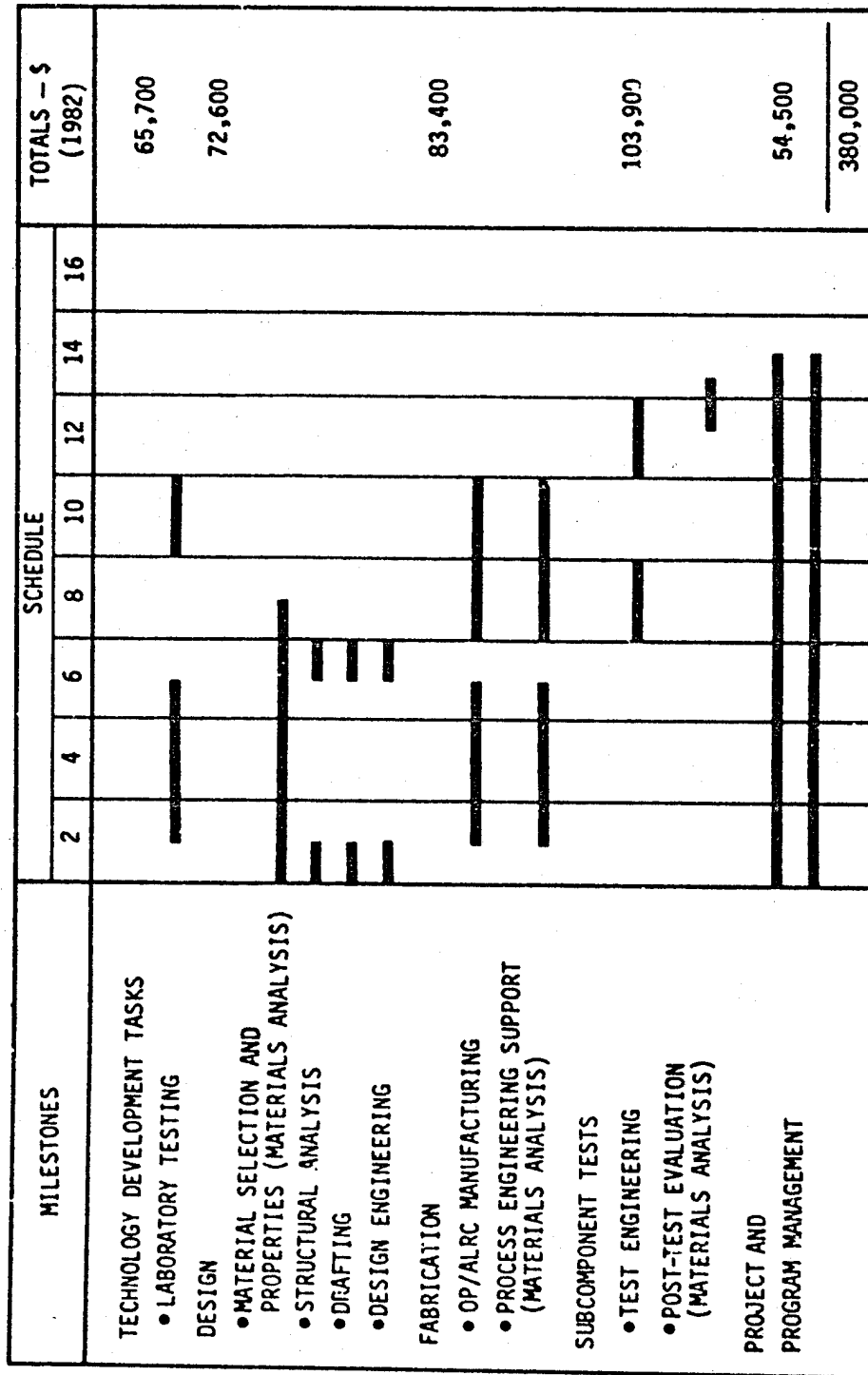


Figure 46. Schedule and Budget for the OTV Valve Housing

VII. C. Program Plans for the Selected Components (cont.)

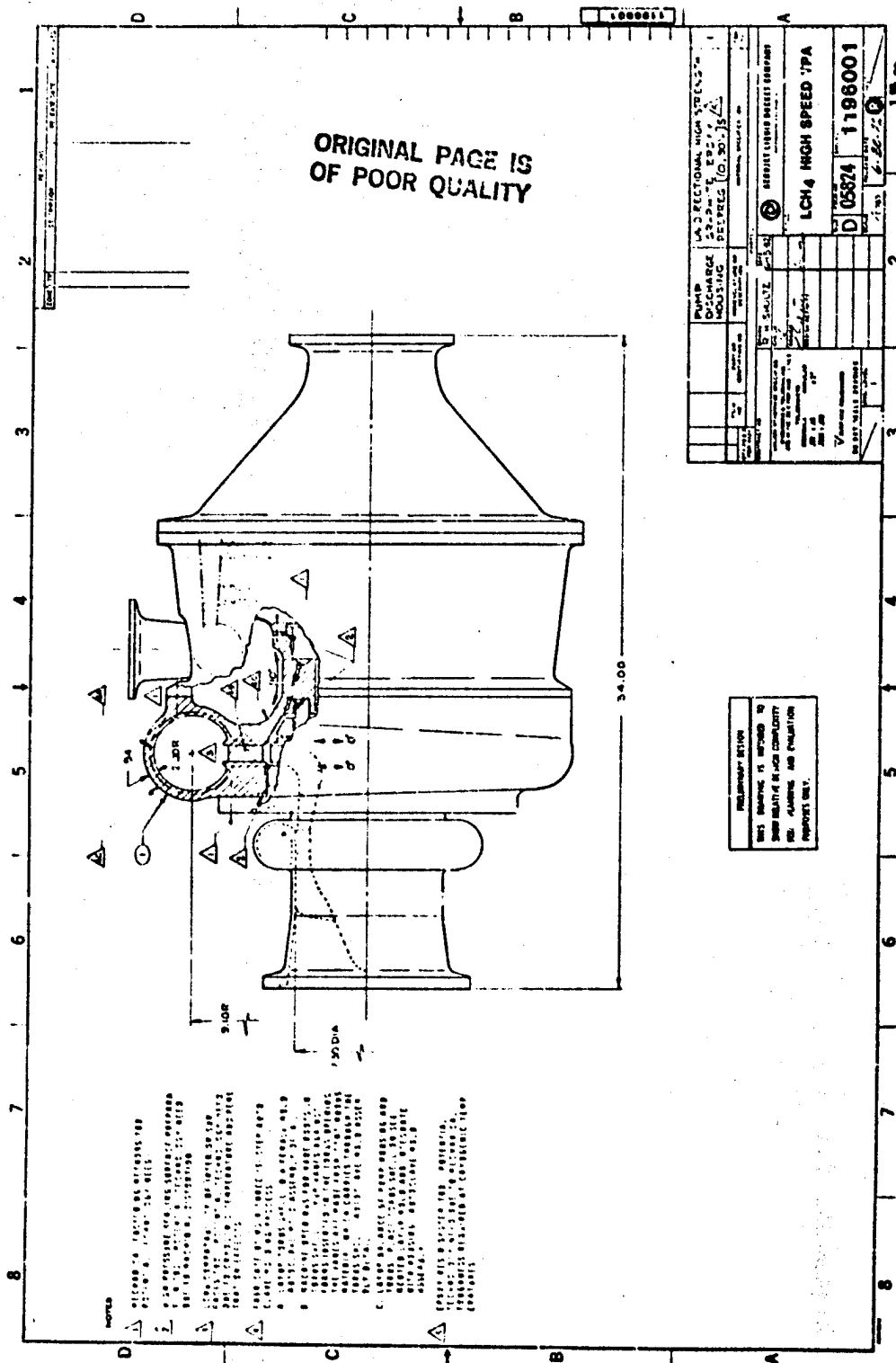
time frame and cost a total of \$380K. The budget was figured on the basis of 1982 company wage rates and includes all management, travel, and reporting expenses. It should be noted that this program could just as easily be split into distinct segments (i.e., technology, design, fabrication, and test) and performed over a 2- or 3-year time period with incremental funding.

2. LCH₄ TPA Impeller Housing

The impeller housing, shown in Figure 47, is the biggest engine weight saver on the 600K booster (2.5% engine weight savings) and is also the most complicated in terms of advancing the state of the art. Its complex shape and propellant exposure would result in the need to address seventeen technology needs before a housing could be successfully fabricated and tested. Its successful fabrication, however, would greatly facilitate the construction of any of the other subcomponents selected in Task III.

Figure 48 shows that the housing torus shell would be laid up in a female mold and autoclave-molded. The openings for the vane roots would be machined in the shell, and the vanes would be laid up against forms inserted in the torus opening and then autoclave-molded. After this, the balance of the pump housing and torus would be laid up and autoclave-molded. The method of applying the barrier coating would be determined as in the case of the OTV valve housing.

Figure 49 summarizes the material and fabrication technology tests which would be performed prior to fabricating the impeller housing. These tests would be similar to those performed for the OTV valve housing, with the addition of vane processing and attachment method testing. The final impeller housing would be proof-tested, cyclic pressure-tested in LCH₄, and destructively burst-tested in LN₂.



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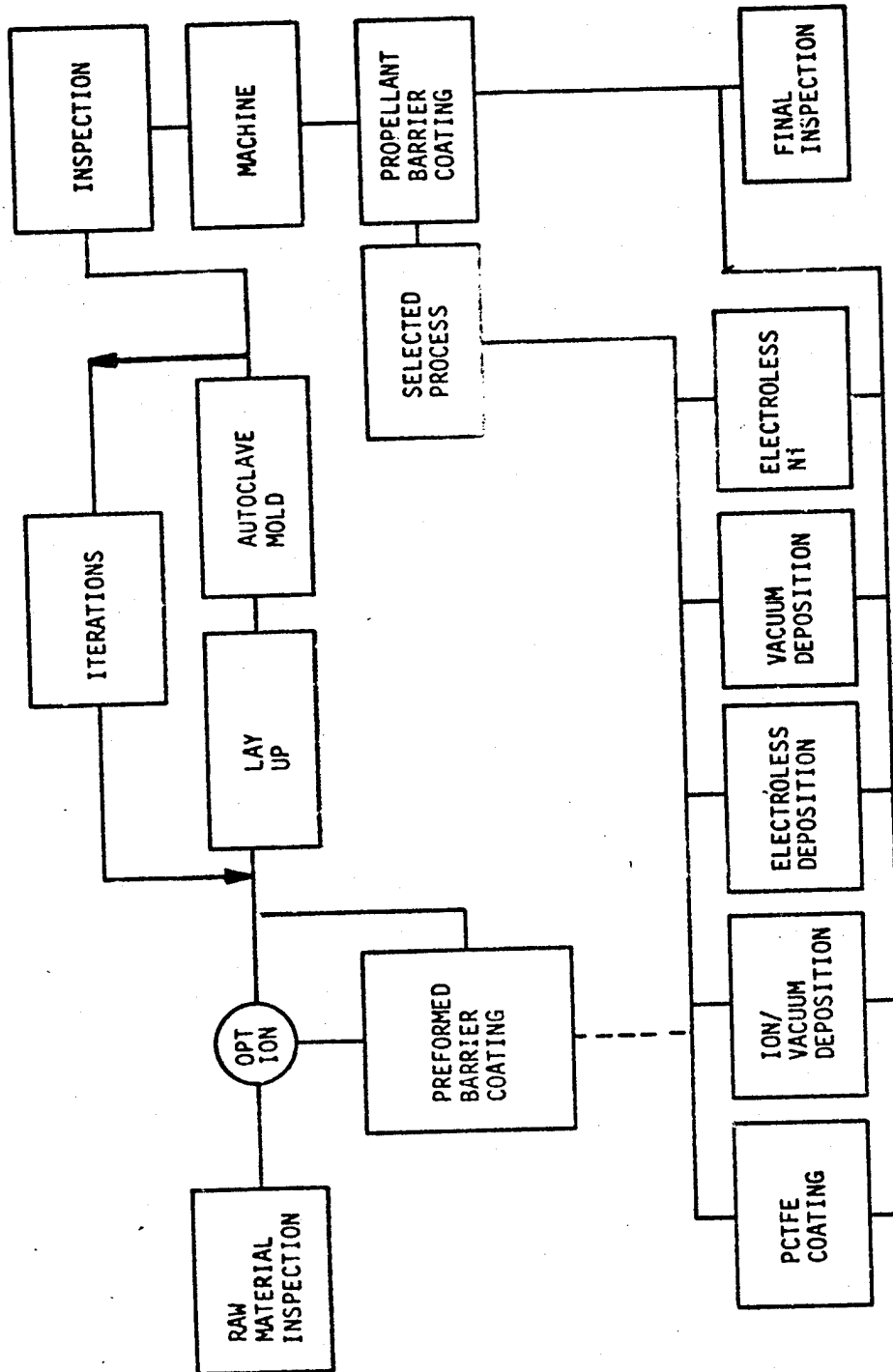


Figure 48. LCH₄ TPA Impeller Housing Fabrication Process Flowchart

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 - PROPELLANT COMPATIBILITY (LONG-TERM DEGRADATION EFFECTS IN LCH_4)
 - LOW TEMPERATURE TOUGHNESS [(STATIC AND CYCLIC FLEXURAL TESTS) (FLAWED AND UNFLAWED SPECIMENS)]
 - BARRIER COATINGS [(FLEXURAL TESTS FOLLOWING LCH_4 EXPOSURE) (ADHESION TESTS AT CRYOGENIC TEMPERATURE)]
 - THERMAL EXPANSION PROPERTIES [(SUBSTRATE AND COATING MATERIALS AT CRYOGENIC TEMPERATURE) (ANISOTROPY DATA)]
 - STRUCTURAL PROPERTIES [(SUBSTRATE AND COATING MATERIALS AT CRYOGENIC TEMPERATURE) (ANISOTROPY DATA)]
- STRUCTURAL ELEMENT TESTS
 - FABRICATION AND MATERIAL PROCESS TRIALS (MECHANICAL FASTENING, SEALING SURFACE FINISHING, VAPE PROCESSING AND ATTACHMENT, FABRICATION SEQUENCING, BARRIER COATING PROCESSING, PLUMBING CONNECTIONS, DETAIL JOINING, MOLD DESIGN, MACHINING)
 - LOW CYCLE (THERMAL) FATIGUE
 - COATING PROCESS OPTIMIZATION (BONDING AIDS AND COATING THICKNESS)
 - KEY INTERFACE SHEAR TESTS IN LN_2
 - CYCLIC PRESSURE AND BURST TESTS
- COMPONENT TESTS
 - PROOF
 - CYCLIC PRESSURE TESTS (LCH_4)
 - BURST TEST (LN_2)

Figure 49. 1196001 LCH_4 TPA Discharge Housing Technology Program and Component Testing

VII. C, Program Plans for the Selected Components (cont.)

The schedule and budget for developing the LCH₄ TPA impeller housing is shown in Figure 50. The program would have a duration of 16 months and cost a total of \$448K. This is the most ambitious and costly of the recommended tasks, but its successful completion would solve the majority of identified technology needs connected with RPC substitution.

3. OTV Nozzle Extension Shaft

The OTV nozzle extension shaft, depicted in Figure 34, shows the greatest percentage of engine weight savings of any of the components selected in Task III (3.3%) and is also fairly simple to fabricate.

Figure 51 shows that the extension shaft would be fabricated by co-pultruding graphite fiber overwrapped with fiberglass. The threads would thereafter be machined in the fiberglass material overlay and lubricated. This simple process would result in a high-strength, lightweight, hollow extension shaft which could be used as part of a nozzle extension mechanism.

Figure 52 contains a summary of the material and fabrication technology testing which would be performed prior to fabricating the shaft. These tests would include 1) fabrication and material process trials, 2) structural properties testing at ambient and cryogenic temperatures (i.e., torsion, bending, tension, shear, and impact testing), and 3) durability tests at ambient temperature. The completed shaft would be subjected to vibration testing, cyclic testing (torsion and bending), and destructive torsion testing.

The schedule and budget for developing the OTV extension shaft are shown in Figure 53. The program would take place over 13 months

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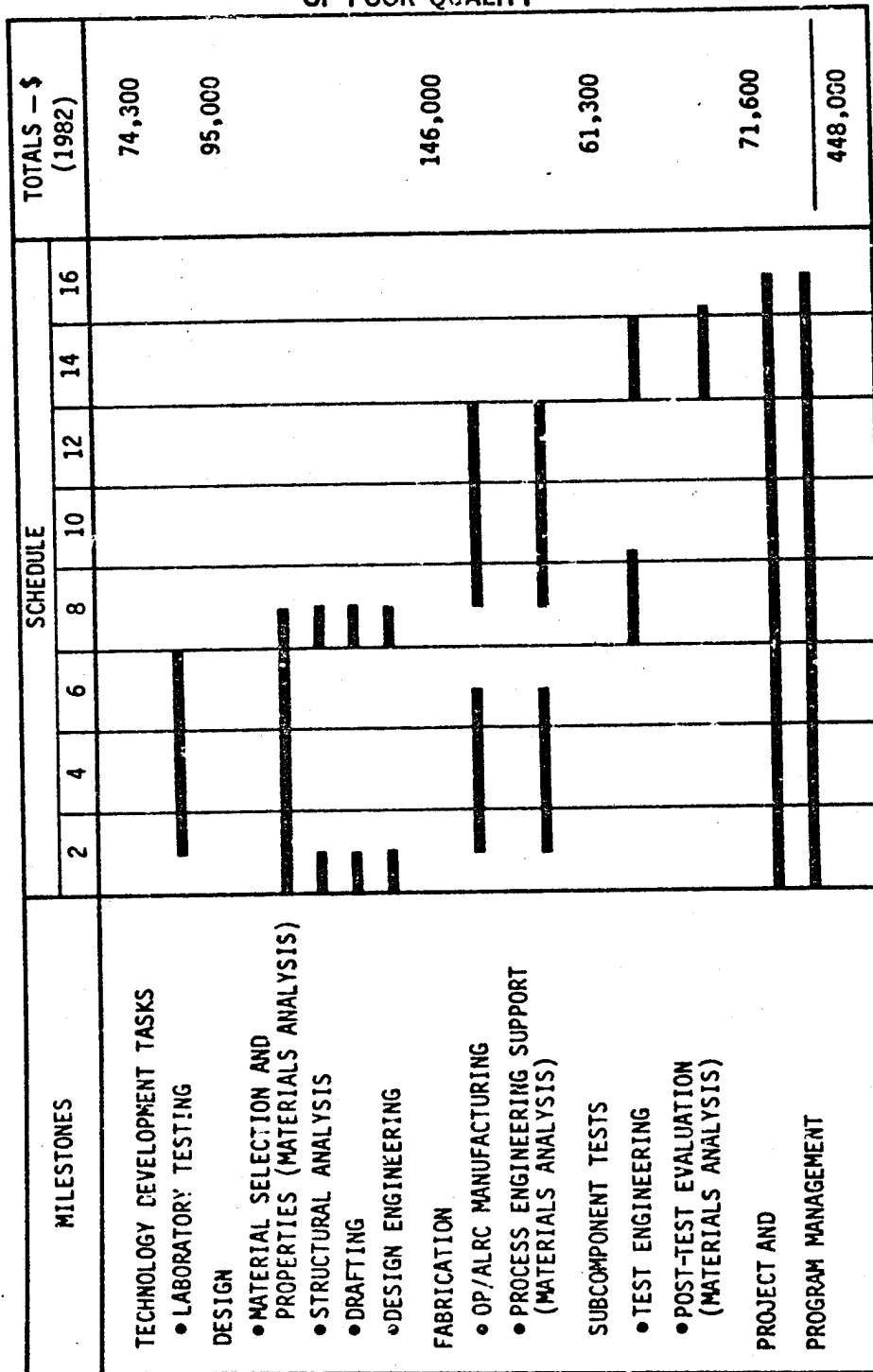


Figure 50. Schedule and Budget for the LCH₄ TPA Impeller Housing

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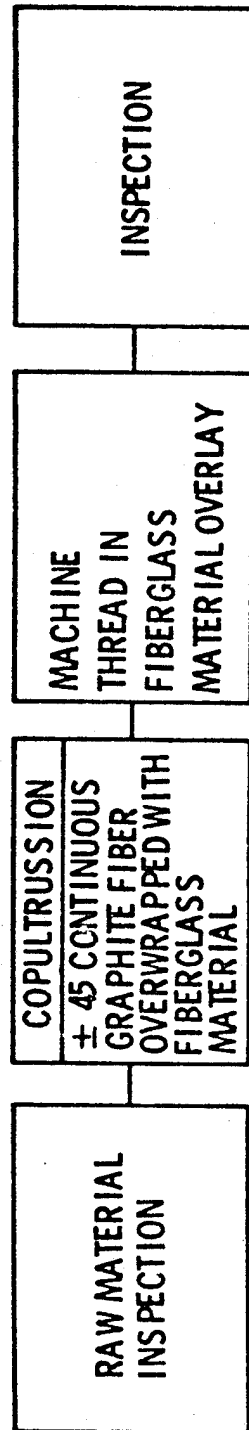


Figure 51. OTV Nozzle Extension Shaft Fabrication Process Flowchart

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- STRUCTURAL ELEMENT TESTS
 - FABRICATION AND MATERIAL PROCESS TRIALS
 - STRUCTURAL PROPERTIES AT AMBIENT TEMPERATURE AND IN LN₂
 - TORSION (INTERLAMINAR SHEAR AND IN-PLANE SHEAR)
 - BENDING (STATIC AND CYCLIC)
 - AXIAL TENSION AND COMPRESSION
 - THREAD SHEAR
 - IMPACT
 - DURABILITY TESTS AT AMBIENT TEMPERATURE
 - UV WEATHEROMETER EXPOSURE
 - THREAD LUBRICANT EVALUATION IN VACUUM
- COMPONENT TESTS AT AMBIENT TEMPERATURE
 - VIBRATION TESTING
 - CYCLIC TESTING (TORSION AND BENDING)
 - DESTRUCTIVE TORSION TEST

Figure 52. 1196006 Shaft, Nozzle Extension Technology Program and
Component Testing

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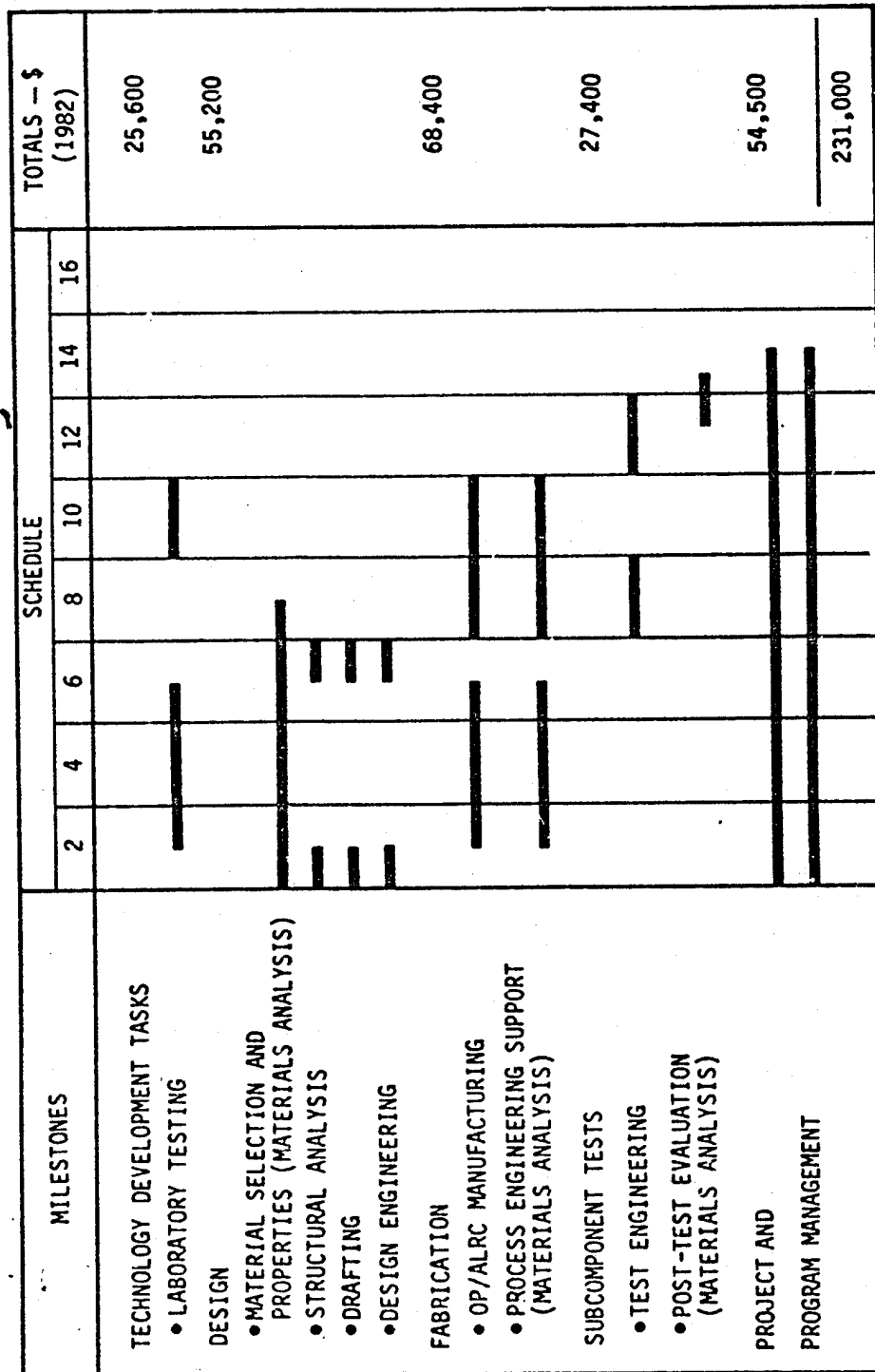


Figure 53. Schedule and Budget for the OTV Nozzle Extension

VII. C. Program Plans for the Selected Components (cont.)

and cost a total of \$231K. This is one of the simplest and least costly programs which could be performed and still result in significant weight savings.

4. OTV Skirt Support Ring

The OTV skirt support ring, shown in Figure 36, shows an engine weight savings of 2.2% and is also simple to fabricate. Additionally, it could be mated with the aforementioned extension shaft to form a sub-assembly.

Figure 54 shows that the support ring would be fabricated by machining a honeycomb core and tape wrapping the honeycomb with graphite-epoxy. The ring would then be cured in an autoclave mold and finish-machined.

Figure 55 contains a summary of the material and fabrication technology testing which would be performed prior to fabricating the ring. These tests would include 1) laboratory coupon tests to explore low temperature toughness and 2) structural element testing (i.e., fatigue, bending, and pull-out testing). The completed support ring would then be subjected to vibration testing, cyclic testing, and destructive bend testing.

The schedule and budget for developing the OTV skirt support ring are shown in Figure 56. The program would take place over 13 months and cost a total of \$231K.

It has been found that combining the development programs for both the OTV nozzle extension shaft and the OTV skirt support ring results in certain economies due to commonality in the technology testing and

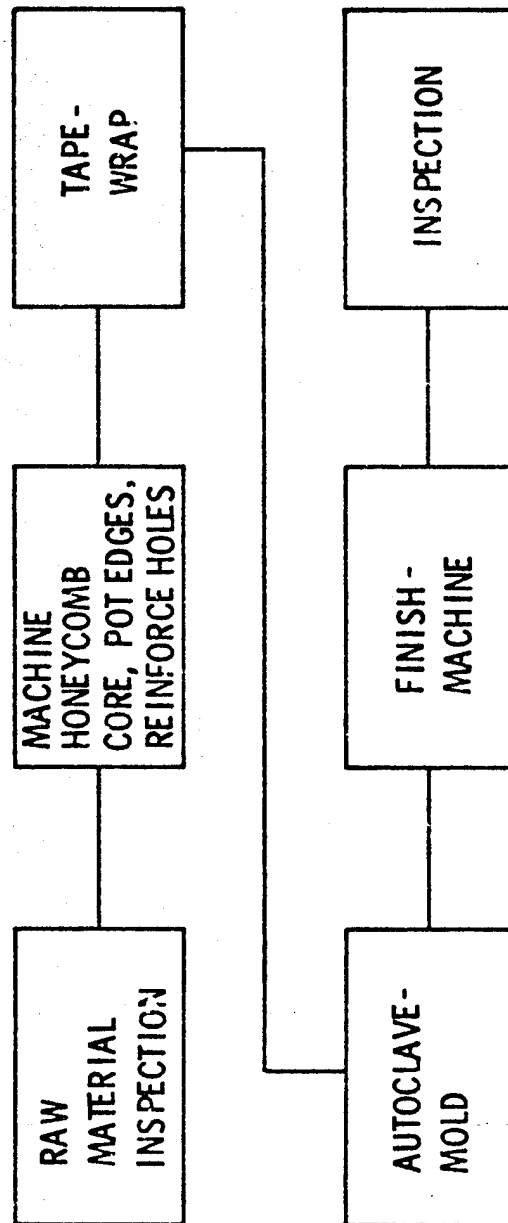


Figure 54. OTV Skirt Support Ring Fabrication Process Flowcart

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- COUPON TESTS
 - LOW TEMPERATURE TOUGHNESS (STATIC AND CYCLIC FLEXURAL TESTS OF FLAWED AND UNFLAWED SPECIMENS AT LN₂ TEMPERATURES)
- STRUCTURAL ELEMENT TESTS
 - FABRICATION AND MATERIAL PROCESS TRIALS
 - LOW CYCLE (THERMAL) FATIGUE
 - BENDING
 - INSERT PULL-OUT AND TORQUE
- COMPONENT TESTS
 - VIBRATION TESTING
 - CYCLIC TESTS [INSERT (TORSIONAL AND AXIAL) AND RING (BENDING)]
 - DESTRUCTIVE BEND TEST

Figure 55. 1196008 Skirt Extension Support Ring Technology Program and Component Testing

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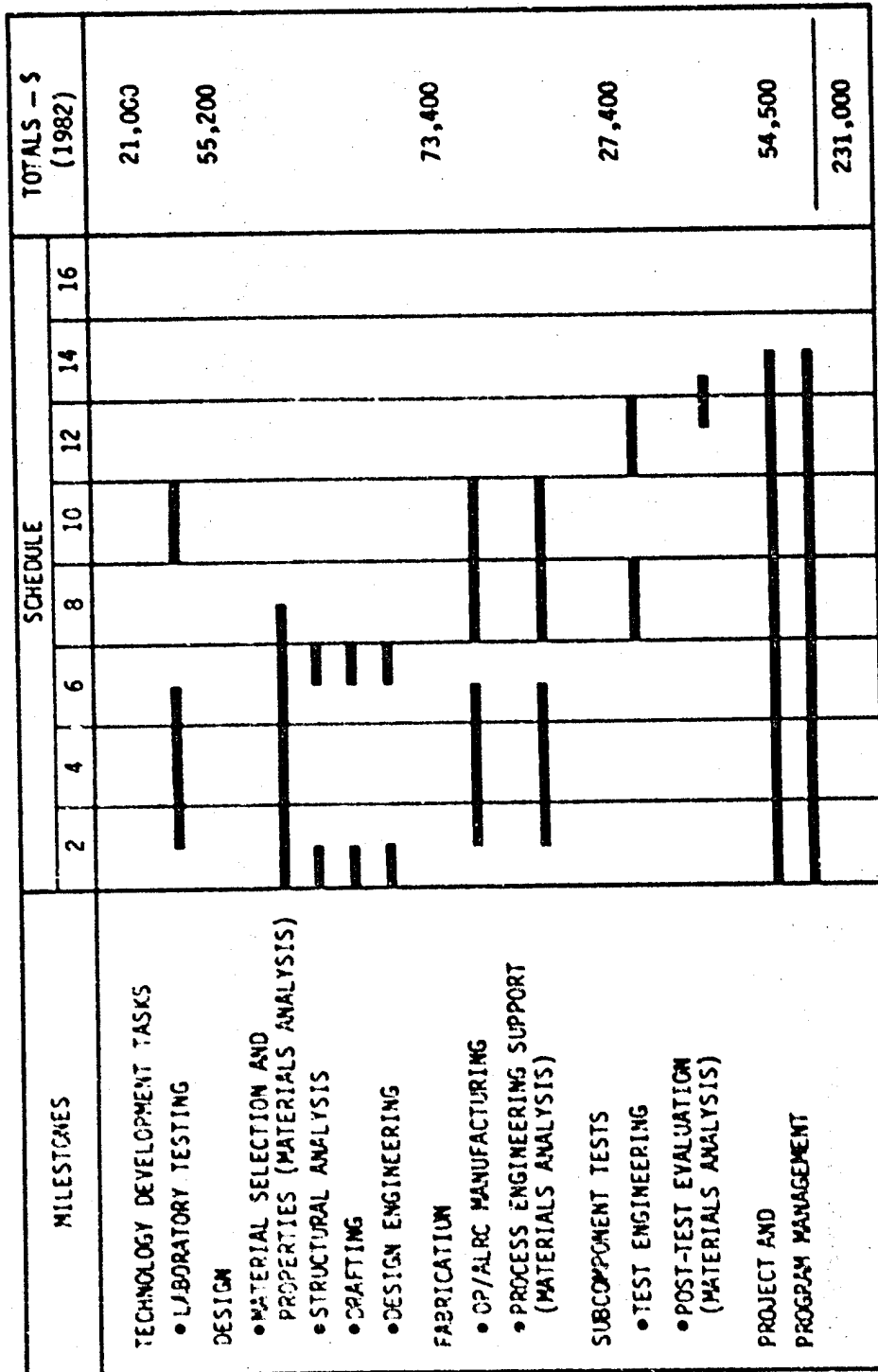


Figure 56. Schedule and Budget for the OTV Skirt Support Ring

VII, C, Program Plans for the Selected Components (cont.)

subcomponent tests. Figure 57 shows that a combined program could be performed in the same 13-month time frame for a cost of \$281K. An added benefit would be the ability to test the two components assembled together as a sub-assembly.

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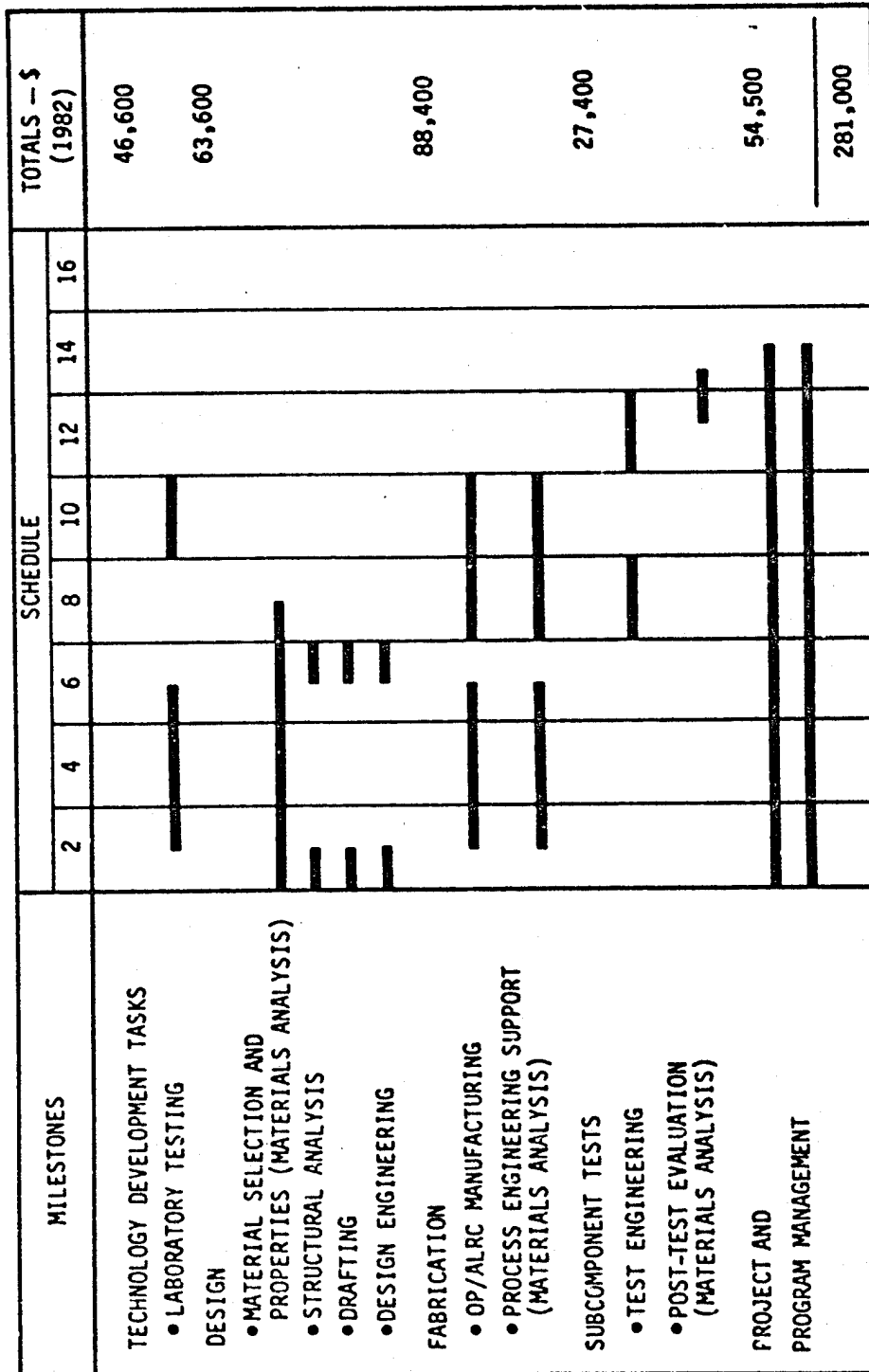


Figure 57. Schedule and Budget for Combining the Support Ring and Extension Shaft

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The following conclusions are drawn from this work:

1. Weight savings of up to 80% are possible on selected components when composite materials are substituted for metal.
2. Engine weight savings from 25 to 30% are possible with use of current composite technology. Future composite technology may save 30 to 40% of the engine weight.
3. A variety of technology needs remain to be explored in substituting composite materials for metallic parts. These technologies can be developed through straightforward laboratory and fabrication test programs.
4. Reinforced plastic composites were selected over metal matrix composites because of their lower cost, greater fabricability, and higher specific strength. If high-temperature applications become more important, or if propellant compatibility becomes a major problem, the use of MMC's would be more clearly indicated.
5. A variety of follow-on programs could be performed to design, fabricate, test, and evaluate rocket engine sub-components made from composite materials. The period of performance would range from 13 to 16 months, with the cost ranging from \$231 to \$448K for the simplest and the most complex tasks, respectively.

VIII, A, Conclusions (cont.)

6. A follow-on program could just as easily be split into distinct segments (i.e., technology testing, design, fabrication, and test) and performed over a 2- or 3-year time period with incremental funding (approximately \$150K per year).

B. RECOMMENDATIONS

The following recommendations are made on the basis of the program results:

1. Conduct technology programs that address the fabrication, material properties, and propellant compatibility of reinforced plastic composites.
2. Fabricate and test an engine subcomponent which shows promising weight savings with the use of composite materials and which solves a wide variety of technology needs (together with, or separate from, the technology programs, depending on schedule and budget restraints).
3. Extend composite technology to additional rocket engine components as the technology is developed.

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APPENDIX A
COMPONENT REQUIREMENT FORMS

A-1



**ADVANCED EXPANDER OTV
COMPONENT REQUIREMENTS**

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components: Gimbal Assembly

Operating Pressure(s)	<u>Subject to 15,000 lb_f thrust</u>
Operating Temperature(s)	<u>Ambient</u>
Propellant Flowrate(s)	<u>-</u>
Start/Shutdown Conditions	<u>-</u>
Envelope (Length)	<u>2.4 in.</u>
Weight	<u>3.3 lb_m</u>
Material(s)	<u>Tit/SS</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components: Chamber

Operating Pressure(s)	<u>Pc = 1200 psia</u>
Operating Temperature(s)	<u> </u>
Propellant Flowrate(s)	Chamber coolant = 3.816 lb/sec, Tube Bundle Flowrate = .674 lb/sec
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u>18 in.</u>
Weight	<u>47.3 lb_m</u>
Material(s)	<u>Zirconium Copper - EF Nickel Closeout</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components: Copper Nozzle

Operating Pressure(s)	<u>17.55 psi (forward), 0.52 psi (aft)</u>
Operating Temperature(s)	<u>730°R</u>
Propellant Flowrate(s)	<u>.674 lb/sec</u>
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u>34.8 in</u>
Weight	<u>27 lbm</u>
Material(s)	<u>copper</u>

TABLE III-I
COMPONENT REQUIREMENTS

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

A-6

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components : Tube Bundle Nozzle

Operating Pressure(s)	<u>2466 psia</u>
Operating Temperature(s)	<u>730°R</u>
Propellant Flowrate(s)	<u>0.674 lb/sec</u>
Start/Shutdown Conditions	<u></u>
Envelope (Length)	<u>30 in.</u>
Weight	<u>38.4 lb_m</u>
Material(s)	<u>347 CRES</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components : Radiation Nozzle

Operating Pressure(s)	<u>Negligible</u>
Operating Temperature(s)	<u>2450°F</u>
Propellant Flowrate(s)	<u>31.56 lbm</u>
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u>49.6 in.</u>
Weight	<u>80 lbm</u>
Material(s)	<u>C-103 Columbium Alloy</u>

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TABLE III-1
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components : Nozzle Deployment System (3 shafts, DC Motor, Support Ring)

Operating Pressure(s)	<u>Ambient</u>
Operating Temperature(s)	<u>Ambient</u>
Propellant Flowrate(s)	<u>--</u>
Start/Shutdown Conditions	<u>_____</u>
Envelope (Length)	<u>60 in.</u>
Weight	<u>72 lb.</u>
Material(s)	<u>_____</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components : Propellant Flow, Control Valves } 8 Total
Modulating Poppet Valve }

Operating Pressure(s)	<u>16 psi - 1450 psi</u>
Operating Temperature(s)	<u>40°R - 600°R</u>
Propellant Flowrate(s)	<u>$\dot{W}_{ox} = 27.05 \text{ lb/sec}$ $\dot{W}_f = 4.51 \text{ lb/sec}$</u>
Start/Shutdown Conditions	
Envelope (Length)	<u>Prop Flow Control Valve 10.12" x 13.75"</u> <u>Mod Poppet Valve 6.4" x 10.9"</u>
Weight	<u>72.7 lb_m</u>
Material(s)	<ul style="list-style-type: none">● Bodies<ul style="list-style-type: none">(1) 6061-T6 Aluminum(2) A356-T6 Aluminum(3) 347 CRES(4) Nitronic 50(5) A-286● Shafts<ul style="list-style-type: none">(1) A-286● Poppets<ul style="list-style-type: none">(1) A-286● Gears<ul style="list-style-type: none">(1) A-286● Springs<ul style="list-style-type: none">(2) 15-5 PH H1150 M● Seal<ul style="list-style-type: none">(1) 302 CRES(1) Filled Teflon

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components: LOX Boost Pump

Operating Pressure(s)	<u>16-56 psia</u>
Operating Temperature(s)	<u>-320°F</u>
Propellant Flowrate(s)	<u>171 GPM</u>
Start/Shutdown Conditions	<u></u>
Envelope (Length)	<u>4.6" X 5.0"</u>
Weight	<u>5.6 lb_m</u>
Material(s)	
Turbine Inlet & Housing	<u>A356</u>
Pump Housing	<u>A356</u>
Impeller & Shaft	<u>15-5PH H1150 M CRES</u>
Bearings	<u>440 C CRES</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lbf</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components : LH₂ Boost Pump

Operating Pressure(s)	<u>18.5 - 50 psia</u>
Operating Temperature(s)	<u>-420°F</u>
Propellant Flowrate(s)	<u>456 GPM</u>
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u>5" X 2.87"</u>
Weight	<u>8.5 lbm</u>
Material(s)	Turbine Inlet & Housing <u>A356 Al</u>
	Pump Housing <u>A356 Al</u>
	Impeller & Shaft <u>Cast Ti 5Al 2.5 Sn ELI</u>
	Bearings <u>440 C CRES</u>
	Preload Springs <u>302 CRES</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components : LOX TPA (Hi Speed)

Operating Pressure(s)	Pump 48-1487 psia Turbine 1512-1326 psia
Operating Temperature(s)	Pump 170°R Turbine 489°R
Propellant Flowrate(s)	<u>194 GPM</u>
Start/Shutdown Conditions	
Envelope (Length)	<u>11.85° X 8.8"</u>
Weight	<u>26.9 lb_m</u>
Material(s)	<ul style="list-style-type: none"> ● Turbine Housing <ul style="list-style-type: none"> (1) A-356 Aluminum (2) Cast 316 CRES (3) Nitronic 50 ● Turbine <ul style="list-style-type: none"> (1) A-286 ● Pump Housing <ul style="list-style-type: none"> (1) A-356 Aluminum (2) Cast 316 CRES ● Seal Housing <ul style="list-style-type: none"> (1) 6061 Aluminum (2) 347 CRES (3) Nitronic 50 ● Pump Impeller & Shaft <ul style="list-style-type: none"> (1) 15-5 PH H1150M (2) INCC 718 ● Bearings <ul style="list-style-type: none"> (1) 440 C CRES

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components: LH₂ TPA (Hi Speed)

Operating Pressure(s)	<u>Pump 49 - 2531 psia</u> <u>Turbine 2344-1522 psia</u>
Operating Temperature(s)	<u>Pump 40°R</u> <u>Turbine 535°R</u>
Propellant Flowrate(s)	<u>547 GPM</u>
Start/Shutdown Conditions	
Envelope (Length)	<u>11.05" x 7.52"</u>
Weight	<u>26.3 lb_m</u>
Material(s)	<ul style="list-style-type: none"> ● Turbine & Pump Housing (one piece) (1) Cast 316 CRES (2) Nitronic 50 ● Pump Impellers (1) Cast Ti BA1 2.5Sn ELI ● Stators/Diffusers (1) Cast Ti 5A1 2.5Sn ELI ● Pump Inlet (1) Cast Ti 5A1 2.5Sn ELI ● Pump Inducer (1) Cast or Wrought Ti 5A1 2.5Sn ELI ● Pump Shaft (1) Wrought Ti 5A1 2.5Sn ELI ● Turbine Exhaust Housing (1) Cast 316 (2) Nitronic 50 ● Turbine (1) A-286 CRES ● Bearings (1) 440 CRES

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TABLE III-1
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components: Misc. Valves & Pneumatic Pack

Operating Pressure(s)	<u>4000 psia</u>
Operating Temperature(s)	<u>Ambient</u>
Propellant Flowrate(s)	<u>None</u>
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u> </u>
Weight	<u>12.6 lbm</u>
Material(s)	<u>Titanium</u>

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TABLE III-1
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components : Lines

Operating Pressure(s)	<u>18 - 1500 psia</u>
Operating Temperature(s)	<u>T_{ox} = 140°R</u> <u>T_f = 40°R - 535°R</u>
Propellant Flowrate(s)	<u>W_{ox} = 27.05 lb/sec</u> <u>W_f = 4.51 lb/sec</u>
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u> </u>
Weight	<u>27.0 lb_m</u>
Material(s)	<u>Titanium</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components : Ignition System

Operating Pressure(s)	<u>1200 psia</u>
Operating Temperature(s)	<u>T_f = 550°R</u> <u>T_{ox} = 140°R</u>
Propellant Flowrate(s)	<u>W_{ox} = .0609 lb/sec</u> <u>W_{H2} = .00152 lb/sec</u>
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u> </u>
Weight	<u>9.2 lb_m</u>
Material(s)	<u>SS/Nickel</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components : Miscellaneous*

Operating Pressure(s)	<u> </u>
Operating Temperature(s)	<u> </u>
Propellant Flowrate(s)	<u> </u>
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u> </u>
Weight	<u>37 lb</u>
Material(s)	<u> </u>

*Electrical Harness - 12.5 lb
Service Lines - 6.5 lb
TPA Protective Bulkhead - 0.4 lb
Attachment Hardware - 15.0 lb
Instrumentation - 2.6 lb

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TABLE III-1
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components: Engine Controller

Operating Pressure(s)	<u>Ambient</u>
Operating Temperature(s)	<u>Ambient</u>
Propellant Flowrate(s)	<u>-</u>
Start/Shutdown Conditions	<u>-</u>
Envelope (Length)	<u>16.8" x 10" x 8"</u>
Weight	<u>35 lbm</u>
Material(s)	<u>Aluminum</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: Advanced Expander (OTV)

Chamber Pressure	<u>1200 psia</u>
Thrust (Vac)	<u>15,000 lb_f</u>
Isp (Minimum) (vac)	<u>475.4 sec.</u>
Propellants	<u>LOX/LH₂</u>
Duty Cycle (Burns)	<u>1200 thermal cycles</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>6.0</u>
Weight	<u>574.4 lb_m</u>

Components: Heat Exchanger

Operating Pressure(s)	<u>1500 - 2300 psia</u>
Operating Temperature(s)	<u>535°R</u>
Propellant Flowrate(s)	<u>Very small amount</u>
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u> </u>
Weight	<u>5.0 lb</u>
Material(s)	<u> </u>

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LOX/LCH₄ ENGINE (CYCLE C)
COMPONENT REQUIREMENTS

A-21

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components : Gimbal System

Operating Pressure(s)	<u>Transmits 600K lb_f thrust</u>
Operating Temperature(s)	<u>Ambient</u>
Propellant Flowrate(s)	<u>--</u>
Start/Shutdown Conditions	<u>--</u>
Envelope (Length)	<u>6.6" Long</u>
Weight	<u>207 lbm</u>
Material(s)	<u>Tit/SS</u>

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TABLE III-1
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb</u>

Components: Injector

Operating Pressure(s)	<u>Pc = 4300 psia</u>
Operating Temperature(s)	<u>Wox = 1432.7 lb/sec</u>
Propellant Flowrate(s)	<u>Wf = 508.43 lb/sec</u>
Start/Shutdown Conditions	<u>--</u>
Envelope (Length)	<u>D = 15.4" L = 10.2"</u>
Weight	<u>611 lbm</u>
Material(s)	<u>Body - Inconel 625 or ARMCO Nitronic -50</u> <u>Manifolds - CRES 347 or Nitronic -50</u> <u>Injector Face - Inconel 625</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components: Combustion Chamber

Operating Pressure(s)	<u>P_c = 4300 psia</u>
Operating Temperature(s)	<u> </u>
Propellant Flowrate(s)	<u>W_T = 1784.51 lb/sec</u>
Start/Shutdown Conditions	<u>--</u>
Envelope (Length)	<u>L' = 15.5" D = 15.44"</u>
Weight	<u>428 lbm</u>
Material(s)	<u>Zirconium Copper</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components: Nozzle

Operating Pressure(s)	<u>6 psi</u>
Operating Temperature(s)	<u>1580°R</u>
Propellant Flowrate(s)	<u>$\dot{W}_T = 1784.51 \text{ lb/sec}$</u>
Start/Shutdown Conditions	<u>-</u>
Envelope (Length)	<u>L = 111.2" Dex = 76.4"</u>
Weight	<u>264 lb_m</u>
Material(s)	<u>Nitronic 50 or A-286</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components : Gas Generator

Operating Pressure(s)	<u>Pc = 4200 psia</u>
Operating Temperature(s)	<u>1860°R</u>
Propellant Flowrate(s)	<u>Wox = 44.75 lb/sec</u> <u>Wf = 111.87 lb/sec</u>
Start/Shutdown Conditions	<u>.</u>
Envelope (Length)	<u>D = 10.5" x L = 14.3"</u>
Weight	<u>76 lbm</u>
Material(s)	<u>Inj. body - Nitronic 50</u> <u>Chamber - Inconel 625</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components: Oxidizer Valves

Operating Pressure(s)	<u>Up to 5300 psi</u>
Operating Temperature(s)	<u>Cryo</u>
Propellant Flowrate(s)	<u>Main Wox = 1432.7 lb/sec</u> <u>GG Wox = 44.75 lb/sec</u>
Start/Shutdown Conditions	
Envelope (Length)	<u>Pump Valve D = 3.1"</u> <u>GG Valve D = 2"</u>
Weight	<u>155 lbm</u>
Material(s)	<u>Aluminum and A-286</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components: Fuel Valves

Operating Pressure(s)	<u>Up to 8000 psi</u>
Operating Temperature(s)	<u>Cryogenic</u>
Propellant Flowrate(s)	<u>Main Wf = 508.43 lb/sec</u> <u>GG Wf = 111.87 lb/sec</u>
Start/Shutdown Conditions	<u>Main Pump Valve Diam = 3.4"</u> <u>GG Valve Diam = 2.7"</u>
Envelope (Length)	<u>133 lbm</u>
Weight	<u>Aluminum & A-286</u>
Material(s)	

TABLE III-I
COMPONENT REQUIREMENTS

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Operating Pressure(s)	$P_D = 231 \text{ psia}$	
Operating Temperature(s)	<u>Tox = 166°R Pump</u>	
	<u>Tox = 166°R Turbine</u>	
Propellant Flowrate(s)	<u>W_{pump} = 1396.5 lb/sec</u>	
	<u>W_{turb} = 215 lb/sec</u>	
Start/Shutdown Conditions	_____	
Envelope (Length)	D _{env} = 26.7"	<u>Line Inlet D = 15.4" Outlet D = 8.2"</u>
	L _{env} = 27.2"	<u>311 lbm</u>
Material(s)	• Shaft	Inconel 718, 15-5 PH H1150M
	• Impeller & Turbine	7075 T-73, Al Alloy
	• Housing	A356 T6, Al Alloy
	• Bolts	A-286
	• Housing Liner	FEP Teflon Fused Coating
	• Bearings	CRES 440C; Haynes Star J Alloy PM

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u> :
Weight	<u>5075 lb_m</u>

Components : Fuel Boost Pump

Operating Pressure(s)	$P_D = 135 \text{ psia}$
Operating Temperature(s)	207°R
Propellant Flowrate(s)	$\dot{W}_{\text{pump}} = 495.4 \text{ lb/sec}$ $\dot{W}_{\text{turb}} = 99 \text{ lb/sec}$
Start/Shutdown Conditions	
Envelope (Length)	$L_{\text{env}} = 20.9''$
Weight	$D_{\text{env}} = 21.9''$
Material(s)	103 lbm All materials same as low speed LOX IPA except teflon coating is not required.

ORIGINAL PAGE 13
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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components : Oxidizer Main Pump

Operating Pressure(s)	<u>5262 psia</u>
Operating Temperature(s)	<u>T_{pump} = 166°R</u> <u>T_{turb} = 1860°R</u>
Propellant Flowrate(s)	<u>W_{pump} = 1396.5 lb/sec</u> <u>W_{turb} = 156.61 lb/sec</u>
Start/Shutdown Conditions	<u>D_{lin} in = 8.2 in.</u> <u>D_{out} = 3.1 in</u>
Envelope (Length)	<u>D_{env} = 26.9"</u> <u>L_{env} = 36"</u>
Weight	<u>895 lbm</u>
Material(s)	<ul style="list-style-type: none"> • Shaft A-286 • Impeller Inconel 718 • High-Pressure ARMCO • Pump & Turbine Hsg. Nitronic-50 • Inducer Housing Inconel 718 • Turbines Inconel 718 • Bolts (pump) A-286 • Bolts (turbine) Waspaloy • Bearings CRES 440C

TABLE III-I
COMPONENT REQUIREMENTS

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

A-32

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TABLE III-1
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components : Hot Gas Manifold

Operating Pressure(s)	<u>363 psia</u>
Operating Temperature(s)	<u>1780°R</u>
Propellant Flowrate(s)	<u>156.61 lb/sec</u>
Start/Shutdown Conditions	<u></u>
Envelope (Length)	<u>D = 6.6"</u>
Weight	<u>23 lbm</u>
Material(s)	<u>Inconel 625</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components: Low Pressure Line

Operating Pressure(s)	<u>15 psia O₂</u> <u>24 psia CH₄</u>
Operating Temperature(s)	<u>Cryo</u>
Propellant Flowrate(s)	<u>W_{ox} = 1396.5 lb/sec</u> <u>W_f = 495.4 lb/sec</u>
Start/Shutdown Conditions	<u>D_{ox} = 15.4"</u> <u>D_f = 10.3"</u>
Envelope (Length)	<u>253 lb</u>
Weight	<u>253 lb</u>
Material(s)	<u> </u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components : High Pressure Lines

Operating Pressure(s)	<u>4000-8000 psia</u>
Operating Temperature(s)	<u>166°R - 1860°R</u>
Propellant Flowrate(s)	<u>W_{ox} = 1396.5 lb/sec</u> <u>P_{ox} = 495.4 lb/sec</u>
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u>Varied - See Calcs</u>
Weight	<u>383 lbm</u>
Material(s)	<u> </u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_{mf}</u>

Components : Ignition Systems

Operating Pressure(s)	<u> </u>
Operating Temperature(s)	<u> </u>
Propellant Flowrate(s)	<u> </u>
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u> </u>
Weight	<u>40 lbm</u>
Material(s)	<u> </u>

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TABLE III-1
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components: Misc. (Frames, fastener, harness, instrumentation, etc).

Operating Pressure(s)	<u> </u>
Operating Temperature(s)	<u> </u>
Propellant Flowrate(s)	<u> </u>
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u> </u>
Weight	<u>174 lbm</u>
Material(s)	<u> </u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components: Controller

Operating Pressure(s)	<u>Ambient</u>
Operating Temperature(s)	<u>Ambient</u>
Propellant Flowrate(s)	<u>-</u>
Start/Shutdown Conditions	<u>-</u>
Envelope (Length)	<u>-</u>
Weight	<u>130 lb</u>
Material(s)	<u>Aluminum</u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components: Pressurization System

Operating Pressure(s)	<u> </u>
Operating Temperature(s)	<u> </u>
Propellant Flowrate(s)	<u>Very Small Amount</u>
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u> </u>
Weight	<u>138 lb.</u>
Material(s)	<u> </u>

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TABLE III-I
COMPONENT REQUIREMENTS

Baseline Engine: LOX/LCH₄ Engine (Cycle C)

Chamber Pressure	<u>4300 psia</u>
Thrust (S.L.)	<u>600,000 lb_f</u>
Isp (Minimum) (S.L.)	<u>309.1 sec.</u>
Propellants	<u>LOX/LCH₄</u>
Duty Cycle (Burns)	<u>100</u>
Cumulative Life	<u>10 hrs.</u>
Mixture Ratio	<u>2.82</u>
Weight	<u>5075 lb_m</u>

Components: Interpropellant Seal

Operating Pressure(s)	<u>5262 psia</u>
Operating Temperature(s)	<u>Pump - 166°R</u> <u>Turbine - 1860°R</u>
Propellant Flowrate(s)	<u>Pump - 1396.5 lb/sec</u> <u>Turbine - 156.61 lb/sec</u>
Start/Shutdown Conditions	<u> </u>
Envelope (Length)	<u> </u>
Weight	<u>90 lbm</u>
Material(s)	<u> </u>

APPENDIX B

REINFORCED PLASTIC COMPOSITE PROPERTIES

POLYMER MATRIX COMPOSITES

MATERIAL IDENTIFICATION	MATERIAL CONSTANTS				ALLOWABLE STRENGTH				MATERIAL COST \$/LB	
	ρ lbs/in ³	E _x psi	E _y psi	E _s psi	ν_x	Tension Ksi	Compression Ksi	Inplane Shear Ksi		Inter-laminar Ksi
1. Graphite epoxy prepreg crossplied (0,90)S	.056	11.5x10 ⁶	11.5x10 ⁶	.8x10 ⁶	.04	100	100	13	13	45
2. Kevlar epoxy Style 181 cloth prepreg	.047	5x10 ⁶	5x10 ⁶	3.3x10 ⁵	.19	50	23	6	3	15
3. Graphite epoxy prepreg crossplied (+45)S	.056	2.5x10 ⁶	2.5x10 ⁶	5.5x10 ⁶	.8	23	23	59.3	13	45
4. Unidirectional Kevlar epoxy prepreg	.054	11x10 ⁶	8x10 ⁵	3.3x10 ⁵	.34	170	40	8.7	6	15
5. Graphite epoxy prepreg Quasi-isotropic laminate (0, ± 45, 90)S	.056	12x10 ⁶	12x10 ⁶	3.1x10 ⁶	.21	105	84	37	13	45
6. 30% chopped fiberglass in Poly (amide - imide)	.067	1.92x10 ⁶	1.92x10 ⁶	3.25x10 ⁶	.38	24	24	-	21.4	20
7. Unidirectional high modulus graphite epoxy prepreg	.056	25x10 ⁶	1.7x10 ⁶	.65x10 ⁶	.30	110	100	9	10	100
8. Unidirectional Boron Epoxy Prepreg	.073	30x10 ⁶	2.7x10 ⁶	.7x10 ⁶	.21	192	353	15.3	13.0	200
9. Fiberglass epoxy Prepreg crossplied (0,90)S	.070	4.7x10 ⁶	4.7x10 ⁶	.3x10 ⁶	.26	140	91	17	9.5	5

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APPENDIX C

METAL MATRIX COMPOSITE PROPERTIES

METAL MATRIX COMPOSITES

MATERIAL IDENTIFICATION	MATERIAL CONSTANTS				ν_x	ALLOWABLE STRENGTH				MATERIAL COST \$/LB
	ρ lbs/in ³	E _x psi	E _y psi	E _s psi		Tension Ksf	Com- pression Ksf	Inplane Shear Ksf	Inter- Laminar Ksf	
Crossplied Boron/Aluminum	.095	25.5x10 ⁶	25.5x10 ⁶	5.6x10 ⁶	.27	172	172	18.0	18.0	325
Silicon Carbide/Aluminum	.103	18x10 ⁶	18x10 ⁶	--	.26	80	120	--	--	200

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APPENDIX D

TASK II EVALUATION FORMS

LOX/LCH₄ 600K BOOSTER
EVALUATION FORMS

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LO₂/CH₄ WEIGHT (lbs): 895 RANKING: 1 TEMP (°F): -290 PRESSURE (PSI): 5262
 COMPONENT: LO₂ TPA % ENGINE WEIGHT: 17 1400

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Inducer Housing	.3	122	9.5/12.4	Compression mold, machine	Tension Bending.	Hybrid Kevlar Graphite Epoxy	100
Inducer	.3	84	10.7/9.3	Compression mold or reaction injection mold, machine	Tension HCF Bending Erosion	Graphite Epoxy	100
Impeller	.3	51	5/16.8	Compression mold or reaction injection mold, machine	Tension HCF Bending Erosion	Graphite Epoxy	100
Impeller Housing	.3	144	15/24	Autoclave mold	Tension Bending	Hybrid Kevlar Graphite Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
90.7	-31.3	4.7	3.4	Excluded	Not a major weight saving
41.7	-42.3	4.9	3.4	Excluded	Not a major weight saving
25.4	-25.6	4.8	3.4	Excluded	Not a major weight saving
49	-95	3.4	3.5	Selected	

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 895 RANKING: 1 TEMP (°F): -290 PRESSURE (PSI): 5262
 COMPONENT: LO₂ TPA % ENGINE WEIGHT: 17 1400

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Turbine Inlet Housing	.3	66	10/27	None	Tension Bending	None	
Turbine Vanes	.3	62		None	Tension Compression Bending HCF	None	
Turbine Rotors	.3	217	7/14	None	Tension Compression Bending HCF	None	
Shaft (2 pc)	.3	87 58	17.2/4 31/.7	Autoclave mold, machine	Torsion Bending HCF	Graphite Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
-	-	-	-	Excluded	High temperature metal or ceramic matrix composite application. Improved performance. No near term weight saving.
-	-	-	-	Excluded	High temperature metal or ceramic matrix composite application. Improved performance. No near term weight saving.
-	-	-	-	Excluded	High temperature metal or ceramic matrix composite application. Improved performance. No near term weight saving.
68.4	-76.6	4.5	2.7	A similar part has been selected for analysis.	

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 895 RANKING: 1 TEMP (°F): -290 PRESSURE (PSI): 5262
 COMPONENT: LO₂ TPA % ENGINE WEIGHT: 17 1400

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Bearings	.3	2.1 1.9	80 mm 75 mm	None		None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
-	-	-	-	Excluded	Ball bearings are not an effective application for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 661 RANKING: 2 TEMP (°F): -253 PRESSURE (PSI): 7953
 COMPONENT: CH₄ TPA % ENGINE WEIGHT: 13 1400

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Inducer Housing	.18	79	9.4/11	Autoclave mold, machine	Tension Bending	Hybrid Kevlar Graphite Epoxy	100
Inducer	.3	63	4.7/6.8	Compression reaction or injection mold, machine	Tension Bending HCF Erosion	Graphite Epoxy	100
Impeller	.3	40	4.0/9.4	Compression reaction or injection mold, machine	Tension Bending HCF Erosion	Graphite Epoxy	100
Impeller Housing	.3	163	13.5/21.4	Autoclave mold	Tension Bending	Hybrid Kevlar Graphite Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/Excluded	Justification For Exclusion
52.4	26.6	4.6	3.9	Excluded	Not a major weight saving
19.9	-43.1	4.9	4.0	Excluded	Not a major weight saving
19.9	20.1	4.7	4.0	Excluded	Not a major weight saver
34	-129	3.9	3.9	Selected	

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 661 RANKING: 2 TEMP (°F): -253 PRESSURE (PSI): 7953
 COMPONENT: CH₄ TPA % ENGINE WEIGHT: 13 1400

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Turbine Inlet Housing	.3	46	14.8/20.3	None	Tension Bending	None	
Turbine Vanes	.3	42	.9/16	None	Tension Bending Compression HCF	None	
Turbine Rotors	.3	138	7.3/16	None	Tension Bending Compression HCF	None	
Shaft (2 pc)	.3 .3	53 33	17/3.1	Autoclave mold	Torsion Bending HCF	Graphite Epoxy	100

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TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
-	-			Excluded	High temperature metal or ceramic matrix composite application. Improved performance. No near term weight saving.
-	-			Excluded	High temperature metal or ceramic matrix composite application. Improved performance. No near term weight saving.
-	-			Excluded	High temperature metal or ceramic matrix composite applications. Improved performance. No near term weight saving.
40.6	-54.4	4.5	3.2	Excluded	A similar part has been selected for analysis.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 661 RANKING: 2 TEMP (°F): -253 PRESSURE (PSI): 7953
 COMPONENT: CH₄ TPA % ENGINE WEIGHT: 13 1400

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Bearings	.3	1.2 .5	60 mm 45 mm			None	None

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TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
				Excluded	Ball bearings are not a cost effective application for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 611 RANKING: 3 TEMP (°F): -290 PRESSURE (PSI): 4300
COMPONENT: Injector % ENGINE WEIGHT: 12 -260

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Body	.3	373	6.2/20	Compression or reaction injection mold, machine	Tension	Kevlar Epoxy	100
Face	.3	17	.18/15.4	Mold, carbonize, machine	Bending LCF	Carbon/Carbon	100
LOX Manifold Cover	.3	33	3/15	Compression or reaction injection mold, machine	Tension	Kevlar Epoxy	100
Fuel Manifold Cover	.3	33	3.8/20.6	Compression or reaction injection mold, machine	Tension	Kevlar Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
282	-91	4.6	4.0	Excluded	Not a major weight saving
21.6	+4.7	4.5	4.4	Excluded	Not a major weight saving
25	-8	4.9	3.2	Excluded	Not a major weight saving
25	-8	4.9	3.7	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 611 RANKING: 3 TEMP (°F): -290 PRESSURE (PSI): 4300
 COMPONENT: Injector % ENGINE WEIGHT: 12 -260

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Housing	.3	51	22.6/24	Compression or reaction injection mold, machine	Tension	Kevlar Epoxy	100
Acoustic Cavity	.3	100	-	Mold, cargonize, machine	Tension	Carbon/Carbon	-

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
24	-27	3.7	3.6	Selected	
130	+30	4.5	4.4	Excluded	Not a major weight saving.

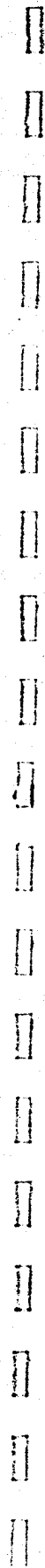


TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 383 RANKING: 4 TEMP (°F): -290 PRESSURE (PSI): 4000-8000
COMPONENT: High Pressure Lines % ENGINE WEIGHT: 8 1400

Part	Material Density (lbs/in ³)	Current Weight (lbs)*	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Tubes	.3	30	12/64	Tape Wrap (tubes)	Tension LCF Buckling	Hybrid Graphite Kevlar Epoxy	
	.3	178**	75/60				
	.3	40**	25/4				
Flanges	.3	80	50/4	Compression mold or reaction injection mold, machine, adhesive bond	Tension Bending Bearing	Graphite Epoxy and metal laminate	
	.3	16**	20/2				
Flex Joints	.3	40		Not a composite application			
		384					
		30 lbs (tubes)					
		80 lbs (flanges)					
		40 lbs (flex joints)					

* All lines

** hot gas line - not composite application

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
12.8	-17.2	4.7	4.0	Excluded	A similar part has been selected for analysis
47.6	-32.4	4.8	4.8	Excluded	A similar part has been selected for analysis

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 364 RANKING: 5 TEMP (°F): -250 PRESSURE (PSI): 4300

COMPONENT: Combustion Chamber % ENGINE WEIGHT: 7 1000

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Liner	.3	154	27/19	Molding, Carbonization, Machine	LCF Compression Induced	Carbon/Carbon	100
Close-Out	.3	61	27/19	Vacuum bag or autoclave bond	Tension Bending	Graphite Epoxy	95-100
Manifolds	.3	50	4.8/23	Compression or autoclave bond	Tension	Kevlar Epoxy	95-100
Support Structure	.3	99	25/25	Autoclave mold	Tension, Bending	Hybrid Graphite Kevlar Epoxy	100

ORIGINAL PAGE 18
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TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
171	+65	3.2	3.9	Excluded	Not a major weight saving
24	-37	4.7	3.9	Excluded	Not a major weight saving
11	-39	4.1	3.7	Selected	
39.6	-59.4	4.6	5.0	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 328 RANKING: 6 TEMP (°F): 1120 PRESSURE (PSI): 6
COMPONENT: Nozzle % ENGINE WEIGHT: 6

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Tube Assembly	.3	109	100/76	None	Tension Bending	None	
Manifold	.3	93	57/5.7	Reaction injection or compression mold, machine	Tension	Kevlar Epoxy	
Manifold	.3	49	30.5/4	Autoclave mold, machine	Tension	Kevlar Epoxy	
Reinforcing Rings	.3	22	-	Autoclave mold, adhesive bond	Tension	Kevlar Epoxy	

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TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/Excluded	Justification For Exclusion
				Excluded	High temperature metal matrix composite application. Improved. No near term weight saving.
58.5	-34.5	4.6	3.7	Excluded	Not a major weight saving
-31	-18	4.7	3.7	Excluded	Not a major weight saving
10.5	-11.5	4.7	5.0	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 328 RANKING: 6 TEMP (°F): 1120 PRESSURE (PSI): 6
 COMPONENT: Nozzle % ENGINE WEIGHT: 6

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Jacket	.3	55	100/76	Wrap and autoclave mold	LCF, Axial Bending	Graphite Epoxy	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
11	-44	4.5	3.9	Selected	

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 311 RANKING: 7 TEMP (°F): -290 PRESSURE (PSI): 231

COMPONENT: LO₂ Boost Pump % ENGINE WEIGHT: 6

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Housing Hybrid	.1	193	27/26.7	Autoclave mold, machine	Tension Bending	Hybrid Cevler Graphite Epoxy	
Inducer Bolt	.3	7	15.4/1.5	None	Tension Compression Shear	None	
Turbine	.1	12	7.9/9.4	Compression or reaction injection mold, machine	Tension Compression Bending HCF	Graphite Epoxy	
Shaft	.3	50	22.8/3.9	Autoclave mold, machine	Torsion Bending HCF	Graphite Epoxy	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/Excluded	Justification For Exclusion
97	-96	4.3	3.2	Selected	
-	-			Excluded	Low interlaminar shear properties limit the effectiveness of threads made of current technology composite materials and no weight saving results.
6	-6	4.9	3.4	Excluded	Not a major weight saving
27	-33	4.6	3.5	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 311 RANKING: 7 TEMP (°F): -290 PRESSURE (PSI): 231

COMPONENT: LO₂ Boost Pump % ENGINE WEIGHT: 6

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Bearings	.3	1	100 mm	None	Bearing Tensile	None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
-	-	-	-	Excluded	Current technology composite materials are not effective in ball bearing applications.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 253 RANKING: 8 TEMP (°F): -260 PRESSURE (PSI): 15-24

COMPONENT: Low Pressure Lines % ENGINE WEIGHT: 5 -290

Part	Material Density (lbs/in ³)	Current Weight (lbs)*	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Tubes	.3	12	11.4/7.3	Autoclave mold, machine	Tension Bending LCF	Hybrid Kevlar Graphite Epoxy	50-99
	.3	19	13.3/10.3				
	.3	54	23/15.4	Compression mold, machine	Tension Bending Bearing	Graphite Epoxy Metal Lamination	50-70
	.3	100	80/8.2				

Flanges

68

Not a composite application

185 (tubes)
68 (flanges)

*All lines

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
71	-113	4.6	4.0	Selected	
41	-27	3.6	4.8	Selected	

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 204 RANKING: 9 TEMP (°F): Ambient PRESSURE (PSI): 600K lbf
 COMPONENT: Gimbal % ENGINE WEIGHT: 4 thrust

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Seat	.18	29	4.7/4.0	Compression or resin injection mold, machine	Dearing Compression	Graphite Epoxy and Metal Lamination	90-95
Body	.3	166	4.0/4.2	Compression or resin injection mold, machine	Bending Bearing	Graphite Epoxy and Metal Lamination	90-95
Block	.3	7	1.4x2.3	Compression or resin injection mold, machine	Compression Bearing	Graphite Epoxy and Metal Lamination	90-95
Shaft	.3	2	4.2/1.0	Compression or resin injection mold, machine	Torsion Bearing Bending	Graphite Epoxy and Metal Lamination	90-95

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
13	-16	4.6	4.5	Selected	
114	-52	4.5	4.5	Excluded	Not a major weight saving
5	-2	4.9	4.5	Excluded	Not a major weight saving
1.6	-.4	4.8	4.5	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 174 RANKING: 10 TEMP (°F): - PRESSURE (PSI):

COMPONENT: Miscellaneous % ENGINE WEIGHT: 3.5

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
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*Not analyzed for composite material applications.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 155 RANKING: 11 TEMP (°F): -290 PRESSURE (PSI): to 5300

COMPONENT: LOX Valves % ENGINE WEIGHT: 3

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Bodies	.1	80	13/13	Reaction or injection mold, machine	Tension	Kevlar Epoxy	95-100
Balls	.3	38	-/5.4	Reaction or injection mold, machine	Bending	Graphite Epoxy	95-100
Shafts	.3	13		Pultruded or autoclave molded	Torsion	Graphite Epoxy	100
Miscellaneous	.3	24		None		None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/Excluded	Justification For Exclusion
60.9	-19.1	4.8	2.8	Excluded	Not a major weight saving
25	-13	4.8	3.0	Excluded	Not a major weight saving
6.2	-6.8	4.9	3.6	Excluded	Not a major weight saving
				Excluded	Nonstructural parts that would not be cost effective if manufactured from composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 138 RANKING: 12 TEMP (°F): - PRESSURE (PSI): -
COMPONENT: Pressurization System % ENGINE WEIGHT: 3

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
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*Not analyzed for composite material application. High temperature metal or ceramic matrix composite application. Improved performance. No near term weight saving.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 133 RANKING: 13 TEMP (°F): -260 PRESSURE (PSI):
 COMPONENT: CH₄ Valves % ENGINE WEIGHT: 2.6

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Bodies	.1	70	14.3/16	Reaction injection or compression mold, machine	Tension	Kevlar Epoxy	95-100
Balls	.3	33	4.4/6.5	Reaction injection or compression mold, machine	Bending	Graphite Epoxy	99-100
Shafts	.3	11	13/1	Pultruded or autoclave molded	Torsion	Graphite Epoxy	100
Miscellaneous	.3	19		None		None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
64	-9	4.9	3.9	Excluded	Not a major weight saving
21.7	-11.3	4.7	3.9	Excluded	Not a major weight saving
5.2	-5.8	4.7	3.9	Excluded	Not a major weight saving
-	-	-	-	Excluded	Nonstructural parts that would not be cost effective if manufactured from composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 130 RANKING: 14 TEMP (°F): Ambient PRESSURE (PSI): Ambient

COMPONENT: Controller % ENGINE WEIGHT: 2.5

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Housing	.1	42	-	Autoclave or vacuum bag mold, machine	Bending	Kevlar Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
32	-10	4.9	5.0	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 103 RANKING: 15 TEMP (°F): -250 PRESSURE (PSI): 135

COMPONENT: Fuel Boost Pump % ENGINE WEIGHT: 2

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Housing	.1	62	21/22	Autoclave mold, machine	Tension Bending	Hybrid Kevlar Graphite Epoxy	95-100
Inducer	.1	15	5.6/10.2	Compression or reaction injection mold	Bending HCF Erosion	Graphite Epoxy	100
Turbine	.3	4	5.7/2.3	Compression or reaction injection mold	Bending HCF Erosion	Graphite Epoxy	100
Inducer Bolt	.3	.5		None		None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
42	-20	4.4	4.2	Excluded	Not a major weight saving
7.5	-7.5	4.8	4.0	Excluded	Not a major weight saving
2.0	-2.0	4.8	4.0	Excluded	Not a major weight saving
				Excluded	Low interlaminar shear properties limit the effectiveness of threads made of current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 103 RANKING: 15 TEMP (°F): -250 PRESSURE (PSI): 135

COMPONENT: Fuel Boost Pump % ENGINE WEIGHT: 2

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Shaft	.3	21	17.2/ 2.3	Autoclave mold	Torsion	Graphite Epoxy	100

None

None

.3

Bearings

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
10	-11	4.87	3.15	Excluded	Not a major weight saving
				Excluded	Ball bearings are not an effective application for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 90 RANKING: 16 TEMP (°F): -290 PRESSURE (PSI): 5262
 COMPONENT: Interpropellant Seal % ENGINE WEIGHT: 2 1400

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
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*Not analyzed for composite material applications.

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TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 76 RANKING: 17 TEMP (°F): -260 PRESSURE (PSI): 363
COMPONENT: Gas Generator % ENGINE WEIGHT: 1.5 -290, 1400

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Injector Body	.3	8	5.6/12.7	Reaction injection or compression mold, machine	Tension	Kevlar Epoxy	95
Manifold	.3	13	5.6/10.5	Reaction injection or compression mold, machine	Tension	Kevlar Epoxy	95
Core	.3	5	1.5/12.7	Reaction injection or compression mold, machine	Compression Bending	Graphite Epoxy	95
Chamber	.3	25	7.2/12.8	Mold, carbonize; machine	Tension Bending	Carbon/Carbon	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
6.0	-2	4.7	4.0	Excluded	Not a major weight saving
9	-4	4.7	3.2	Excluded	Not a major weight saving
3.3	-1.7	4.9	3.6	Excluded	Not a major weight saving
25	+0.0	4.4	4.4	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LCY/CH ₄	WEIGHT (lbs): 76	RANKING: 17	TEMP (°F): -260	PRESSURE (PSI): 363			
COMPONENT: Gas Generator	% ENGINE WEIGHT: 1.5	-290, 1400					
Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Elements	.3	25	7.4/1.3	Compression Mold	Compression 30% Chopped 100 fiberglass poly (Amide-imide)		

TABLE 1 (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
9.5	-15.5	4.5	4.0	Excluded	Not a major weight savings

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 40 RANKING: 18 TEMP (°F): PRESSURE (PSI):

COMPONENT: Ignition System % ENGINE WEIGHT: .7

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
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*Not analyzed for composite material applications

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: LOX/CH₄ WEIGHT (lbs): 23 RANKING: 19 TEMP (°F): 1300 PRESSURE (PSI): 363

COMPONENT: Hot Gas Manifold % ENGINE WEIGHT: .5

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Manifold	.3	23	-	Mold, carbonize, machine	Tension	Carbon/ Carbon	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
29.4	+5.4	3.2	3.9	Excluded	Not a major weight saving

15K QTV EVALUATION FORMS

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander WEIGHT (lbs): 80 RANKING: 1 TEMP (°F): 245° PRESSURE (PSI): Negligible
 COMPONENT: Nozzle-Radiation Cooled % ENGINE WEIGHT: 14

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Nozzle	.3	80	65/50	Molding, Carbonization, Machining	Beam Bending, Interlaminar Shear Stress	Carbon/ Carbon	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
130	+50	3.2	3.9	Exclude	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Valves & Actuators
WEIGHT (lbs): 72.8 RANKING: 3 TEMP (°F): -370° to 140° PRESSURE (PSI): 16-1450
% ENGINE WEIGHT: 12.6

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
2 Valve Bodies	.18	10	6.8/4	Compression mold, machine	Tension	Kevlar Epoxy	95-100
4 Actuator Bodies	.18	29	11/2.4	Compression mold, machine	Tension	Kevlar Epoxy	100
Actuator End Closures	.18	7.8	.7/2.4	Compression mold, machine	Bending	Kevlar Epoxy	100
4 Gates	.3	5.0	2.2	Compression mold, machine	Bending	Graphite polyimide amide	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
2.6	-7.4	4.8	2.8	Selected	
8.7	-20.3	4.8	4.0	Excluded	Not a major weight saving
2.2	-5.6	4.8	5.0	Excluded	Not a major weight saving
1.8	-3.2	4.8	3.0	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
 COMPONENT: Valves & Actuators
 WEIGHT (lbs): 72.8 RANKING: 2 TEMP (°F): -370° to 140°
 % ENGINE WEIGHT: 12.6 PRESSURE (PSI): 16-1450

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Shafts	.3	10	2.5	Compression mold, machine	Shear	Graphite Epoxy	100
Gears	.3	10	-	Compression mold, machine	Bending	Graphite Epoxy	100
3 Springs	.3	1	5/3	None	Shear	None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
3.6	-6.4	4.8	3.6	Selected	
3.6	-6.4	4.8	3.6	Selected	
-	-	-	-	Excluded	Springs are not a cost effective application for composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander WEIGHT (lbs): 72 RANKING: 4 TEMP (°F): Ambient PRESSURE (PSI): Ambient
 COMPONENT: Nozzle Deployment System % ENGINE WEIGHT: 12.5

Part	Material Density (lbs/in ³)	Current weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
3 Extension Shafts	.3	24	53/1	Pultrusion	Tension, Compression	Graphite Epoxy	100
Support Ring	.3	27	1/37	Autoclave mold	Tension Bending	Graphite Epoxy	100
Gear Box	.3		3.5/3	None		None	
Ball Screws	.3	21	3/3	None		None	
Flex Shafts	.3		.5/25	None		None	

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TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/Excluded	Justification For Exclusion
4.9	-19.1	4.9	3.8	Select	
14	-13	4.6	5.0	Select	
				Exclude	Nonstructural parts that would not be cost effective if manufactured from composite materials.

TABLE 1
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Combustion Chamber
WEIGHT (lbs): 74.3 RANKING: 2 TEMP (°F): 1000° PRESSURE (PSI): 1200
% ENGINE WEIGHT: 13

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Liner	.3	20.4	22/8.4	Molding, Carbonization, Machining	LCF, Compression Induced	Carbon/Carbon	100
Close-Out	.3	9.4	22/10	Vacuum bag or autoclave mold	Tension, Bending	Graphite Epoxy	95-100
Manifolds	.3	22.5	3/11 3/30	Compression or autoclave mold	Tension	Kevlar Epoxy	95-100
Support Structure	.3	22	24/12	Autoclave mold, machine	Bending (axial) Tension (radial)	Hybrid Graphite Kevlar Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/Excluded	Justification For Exclusion
33	+12.6	3.2	3.9	Excluded	Not a major weight saving
3.7	-5.7	4.7	3.9	Excluded	Not a major weight saving
14	-8.5	4.7	2.8	Excluded	Not a major weight saving
5.6	-16.4	4.5	5.0	Selected	

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
 COMPONENT: Nozzle-Tube Bundle
 WEIGHT (lbs): 38.4 RANKING: 5 TEMP (°F): 270° PRESSURE (PSI): 2466
 % ENGINE WEIGHT: 6.6

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Tube Assembly	.3	29.4	34.4/ 36.6	Tape wrap tubes*	Tension, LCF, Buckling	Hybrid Graphite Kevlar Epoxy	20-30
4 Reinforcing Rings	.3	3	35/2 29/2 24/2 18/2	Autoclave mold	Tension	Kevlar Epoxy	100
Manifold	.3	6	1.3/12	Compression mold, adhesive bond	Tension	Kevlar Epoxy	100

* Reinforcement of Tubes

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
*	*	-	-	Excluded	Not a major weight saving
1.2	-1.8	4.7	5.0	Excluded	Not a major weight saving
3.8	-2.2	4.5	3.1	Excluded	Not a major weight saving

* Negligible weight benefit from overlapping steel tube bundle with composite.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Propellant Lines
WEIGHT (lbs): 37
% ENGINE WEIGHT: 6.4
RANKING: 6
TEMP (°F): -290°
PRESSURE (PSI): 18-1500
-420

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Tubes	.3	9	35/2.5 30/1.5	Tape wrap	Tension, Bending	Hybrid Kevlar, Graphite Epoxy	90-100
Flanges	.3	10	1.5/4 1/2	Compression mold, adhesive bond	Tension, Bending	Graphite Epoxy Metal Laminate	50-75
Flex Joints	.3	18	2.5/3 2/2	None	Tension Bending	Hybrid Kevlar, Graphite Epoxy	90-100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
3.8	-5.2	4.7	4.0	Excluded	Not a major weight saving
6	-4	4.7	4.6	Excluded	Not a major weight saving
7.6	-10.4	4.7	4.0	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: Controller
WEIGHT (lbs): 35
% ENGINE WEIGHT: 6
RANKING: 7
TEMP (°F): Ambient
PRESSURE (PSI): Ambient

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Case	.1	11	17x8x10	Autoclave mold		Kevlar Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
8.4	-2.6	5.0	5.0	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
 COMPONENT: Injector
 WEIGHT (lbs): 30.6 RANKING: 8 TEMP (°F): PRESSURE (PSI): 1200-1434
 % ENGINE WEIGHT: 5.3

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Body	.3	21	3.2/6.5	Compression or reaction injection mold	Tension	Kevlar Epoxy	95-100
Face	.3	1.0	05/5.6	Molding, carbonization, machine, adhesive bond	LCF, bending	Carbon/ carbon	100
Co-axial Elements	.3	1.2	.18/2.3	Reaction injection mold or compression mold, or pultruded/ wrapped tube	Tension, Compression	Graphite Epoxy	100
Manifold	.3	5	2.3/7.9	Compression or reaction injection mold	Tension	Kevlar Epoxy	95-100

TABLE 1 (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
16	-5	4.7	3.8	Excluded	Not a major weight saving
1.0	+.3	4.7	4.4	Excluded	Not a major weight saving
.5	-.7	4.7	3.1	Excluded	Not a major weight saving
3.8	-1.2	4.7	3.6	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander WEIGHT (lbs): 30.6 RANKING: 8 TEMP (°F): PRESSURE (PSI): 1200-1434
 COMPONENT: Injector % ENGINE WEIGHT: 5.3

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
2 Clevises	.3	2.4	2.9/1.6	Compression or reaction injection mold	Tension, Bending, Shear, Bearing	Graphite Epoxy, 10% Steel	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
1.8	-.6	4.7	4.8	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander WEIGHT (lbs): 25.1 RANKING: 9 TEMP (°F): -290 PRESSURE (PSI): 48-1487
 COMPONENT: LOX TPA % ENGINE WEIGHT: 4.7 30 1326-1512

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Pump Housing	.1	5.4	33/6.2	Compression mold, machine	Tension, Bending	Hybrid Graphite Kevlar Epoxy	95-100
Seal Housing	.1	7.0	5/1/4.2	Compression mold, machine	Tension, Bending	Kevlar Epoxy	100
Turbine Housing	.1	4.0	3.9/8.8	Compression mold, machine	Tension, Bending	Hybrid Graphite Kevlar Epoxy	95-100
Impeller	.1	.2	1/18	Compression or reaction mold	HCF, Tension, Bending	Graphite Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
2.4	-3	4.7	3.8	Excluded	Not a major weight saving
5.3	-1.7	4.8	3.5	Excluded	Not a major weight saving
1.8	-2.2	4.8	4.0	Excluded	Not a major weight saving
.1	-.1	4.9	3.8	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: LOX TPA
WEIGHT (lbs): 25.1 RANKING: 9 TEMP (°F): -290 PRESSURE (PSI): 48-1487
% ENGINE WEIGHT: 4.7 30 1326-1512

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Shaft	.3	2.0	5.8/1.2	Spiral tape wrap, autoclave mold, machine	HCF, Tension, Bending	Graphite Epoxy	100
Turbine	.3	4.0	2.8/6.3	Compression or resin injection mold	HCF, Tension, Bending	Graphite Epoxy	100
Bearing	.3	2.5	None	None	Tension Bearing	None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
.9	-1.1	4.7	3.9	Excluded	Not a major weight saving
2	-2	4.9	3.8	Excluded	Not a major weight saving
				Excluded	Ball bearings are not a cost effective application for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander WEIGHT (lbs): 21.5 RANKING: 10 TEMP (°F): -420 PRESSURE (PSI): 49-2531
COMPONENT: LH₂ TPA % ENGINE WEIGHT: 4.6 75 2344-1522

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Propose. Fab. Meth.	Critical Failure Mode	Proposed Material	Volume Fraction (%)
LH ₂ Inlet Housing	.18	4.0	2.8/5.8	Compression reaction or injection mold, machine	Tension, Bending	Hydrid Kevlar Graphite Epoxy	95-99
Pump Housing	.18	8.5	6.8/6.6	Compression mold, machine	Tension, Bending	Graphite Epoxy	95-99
Inducer	.18	.1	1.6/3.8	Compression mold, resin injection, machine	HCF, Tension, Bending	Graphite Epoxy	100
Impellers	.18	3.0	1.3/3.4	Compression mold, resin injection, machine	HCF, Tension, Bending	Graphite Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
1.8	-2.2	4.9	4.0	Excluded	Not a major weight saving
3.8	-4.7	4.8	4.0	Excluded	Not a major weight saving
.05	-.05	4.9	3.6	Excluded	Not a major weight saving
1.5	-1.5	4.9	3.6	Excluded	Not a major weight saving

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: LH₂ TPA
WEIGHT (lbs): 21.5 RANKING: 10 TEMP (°F): -420 PRESSURE (PSI): 49-2531
% ENGINE WEIGHT: 4.6 75 2344-1522

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Turbine Exit Housing	.1	3.7	2.0/3.8	Compression mold, machine	Tension, Bending	Graphite Epoxy	100
Shaft	.3	1.4	7.8/.8	Tape wrap, machine	HCF, Tension, Bending	Graphite Epoxy	100
Turbines	.3	.6	.9/2.8	Compression mold, machine	HCF, Tension, Bending	Graphite Epoxy	100
Bearings	.3	.2	12 mm 40 mm	None	Bearing Tension	None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
1.4	-2.3	4.8	4.3	Excluded	Not a major weight saving
.7	-.7	4.7	3.3	Excluded	Not a major weight saving
.3	-.3	4.9	3.8	Excluded	Not a major weight saving
Excluded					Ball bearings are not a cost effective application for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
 COMPONENT: Misc. Valves and Pneu. Pack % ENGINE WEIGHT: 2.2
 WEIGHT (lbs): 12.6 RANKING: 11 TEMP (°F): PRESSURE (PSI):

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
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*

*Not analyzed for composite material applications.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
 COMPONENT: Ignition System
 WEIGHT (lbs): 9.2 RANKING: 12 TEMP (°F)
 % ENGINE WEIGHT: 1.6 PRESSURE (PSI): 1200

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
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*

*Not analyzed for composite material applications

TABLE 1
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
 COMPONENT: LH₂ Boost Pump
 WEIGHT (lbs): 8.5 RANKING: 13 TEMP (°F): -420 PRESSURE (PSI): 18.5-50
 % ENGINE WEIGHT: 1.4

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia: (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Turbine- Impeller Housing	.1	3.6	2.3/5.6	Compression mold, machine	Tension, Bending	Hybrid Kevlar Graphite Epoxy	95-100
Exit Housing	.1	4.1	2.7/5	Compression mold, machine	Tension, Bending	Hybrid Kevlar Graphite Epoxy	100
Turbine- Impeller	.1	.3	1.4/4.4	Compression mold, machine	HCF, Tension, Bending	Graphite Epoxy	100
Impeller Bolt	.3	.1	2.5/.3	None	Tension, Compression	None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/Excluded	Justification For Exclusion
1.6	-2.0	4.8	3.7	Excluded	Not a major weight saving
1.8	-2.3	4.8	3.7	Excluded	Not a major weight saving
.15	-.15	4.9	3.6	Excluded	Not a major weight saving
				Excluded	Low interlaminar shear properties limit the effectiveness of threads made of current technology composite materials and no weight savings results.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: LH₂ Boost Pump
WEIGHT (lbs): 8.5 RANKING: 13 TEMP (°F): -420 PRESSURE (PSI): 18.5-50
% ENGINE WEIGHT: 1.4

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Shaft	.3	.4	3.8/.6	Autoclave mold, machine	Tension, Bending	Graphite Epoxy	100
Bearings	.3	.08	17mm	None	Bearing Tension	None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
.19	-.22	4.7	3.3	Excluded	Not a major weight saving

Ball bearings are not a cost effective application
for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander
COMPONENT: LOX Boost Pump
WEIGHT (lbs): 5.6 RANKING: 14 TEMP (°F): -320 PRESSURE (PSI): 16-56
ENGINE WEIGHT: 1.0

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/ Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Turbine- Impeller Housing	.1	2.4	1.9/5.5	Compression mold, machine	Tension, Bending	Hybrid Kevlar Graphite Epoxy	95-100
Exit Housing	.1	2.7	3.4/3.1	Compression mold, machine	Tension, Bending	Hybrid Kevlar Graphite Epoxy	100
Impeller Shaft	.1	.3	3.4/3.1	Compression mold	Tension, Bending	Graphite Epoxy	100
Bearings	.3	.08	15 mm	None	Bearing, Tension	None	

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
1.05	-1.35	4.6	3.2	Excluded	Not a major weight saving
1.2	-1.5	4.8	3.2	Excluded	Not a major weight saving
.15	-.15	4.7	3.5	Excluded	Not a major weight saving
				Excluded	Ball bearings are not a cost effective application for current technology composite materials.

TABLE I
COMPONENT ASSESSMENT AND IDENTIFICATION

ENGINE: Advanced Expander WEIGHT (lbs): 5 RANKING: 15 TEMP (°F): 70 PRESSURE (PSI): 1500-2300
 COMPONENT: Heat Exchanger % ENGINE WEIGHT: .8

Part	Material Density (lbs/in ³)	Current Weight (lbs)	Length/Dia. (in)	Proposed Fab. Method	Critical Failure Mode	Proposed Material	Volume Fraction (%)
Outer Shell	.3	3.5	3/6.4	Tape Wrap	Tension	Graphite Epoxy	100
Inner Shell	.3	1.5	3/4.0	Autoclave mold, adhesive bond, machine	Tension	Graphite Epoxy	100

TABLE I (continued)

New Weight (lbs)	Delta Weight (lbs)	Cost Rating	Maintenance Rating	Selected/ Excluded	Justification For Exclusion
1.75	-1.75	4.7	3.6	Excluded	Not a major weight saving
9.75	-.75	4.7	3.6	Excluded	Not a major weight saving

APPENDIX E
VENDOR TRIP MEMOS



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Materials Analysis

REPORT NO. MA-82-144
DATE 25 June 1982

WORK REQUESTED BY D. C. Judd	DEPT. 9733	PAGE 1 OF 4
SUBJECT Trip Report - Composite Material Fabricators (June 21-22)		TABLES: 2
		FIGURES:
PROGRAM Composite Material Applications to Liquid Rocket Engines	W.O. NO. 2418-03-000	ENCLOSURES:
PART NAME Conceptual Design Assessment	PART NO. Task III	S/N MATERIAL Composites

PURPOSE:

To meet with fabricators of composite materials to present ALRC conceptual designs for composite parts, to obtain their comments on producibility, and to assess their fabrication capabilities.

SUMMARY:

Six contractor facilities were visited during a two day trip to Los Angeles. In these meetings it was explained that a significant weight savings (between 30 and 40 percent) can be realized by substituting composite materials for metals in liquid rocket engines. All six contractors indicated that they would be interested in helping ALRC develop rocket engine parts.

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	G. R. Janser <i>G. R. Janser</i>
	APPROVED BY
	<i>[Signature]</i> VEPICK MANAGER MATERIAL ANALYSIS SECTION

INTRODUCTION:

The current NASA contract to study composite material applications in liquid rocket engines has provisions for recommending designs for a minimum of two parts for a follow-on development program. A description of this follow-on program is required including detail fabrication plans. During the visits to the six subcontractor facilities, subcontractor participation in the follow-on program was discussed. The preliminary designs of seven rocket engine parts to be made with composites were reviewed. Each contractor was asked to assess his capability to make the parts together with anticipated processing difficulties.

DISCUSSION:

The preliminary designs reviewed by the six subcontractors fall into three categories of producibility:

- (1) Parts whose fabrication is straightforward.
- (2) Parts that require a process development program to establish parameters for controlling fiber geometry.
- (3) Parts that require redesign in order to successfully fabricate (Note 1A, Table I).

Table I summarizes the position of each subcontractor on these parts; it shows the processes available at each facility for manufacturing the part and the contractor's opinion of producibility. For five of the designs (1196001, 1196002, 1196003, 1196005, and 1196007), the complexity of the parts and the lack of design detail make the assessment of producibility difficult. Two of these designs (1196003 and 1196005) had enough obvious difficulties to establish that a redesign would be necessary. It was assumed that the redesigned part would be satisfactory for manufacturing if the subcontractor consulted with the designer.

Swedlow Inc. indicated that they could assume responsibility for part design. This suggestion was made during the review of the injector housing (1196007). They feel that the high pressures and propellant flows dictate extraordinary methods of structural analysis.

Four subcontractors (Swedlow, HITCO, Reynolds and Taylor, and M.C. Gill) have excellent facilities for producing parts using composite materials. Two contractors (Swedlow and HITCO) also have the capability to design with composite materials.

The subcontractors have indicated that the response time to an RFQ for participation in a development program would be three weeks or less. To prepare a quote, they would require an SOW and a detail design of the part to be developed. Additional technical meetings would be helpful to discuss program requirements and familiarize the subcontractors with rocket engine components. HITCO made the suggestion that one development part might be a mock-up combining the design features and technology needs of several parts. This approach would concentrate the objectives of the program in one part and set of tooling to reduce costs.

Table II lists the persons contacted during the visits along with the product lines of the companies.

CONCLUSIONS:

1. All six contractors have potential to help ALRC build rocket engine parts out of composite materials.
2. HITCO, Swedlow, and M.C. Gill are large diversified manufacturers with significant manufacturing research capability. Reynolds and Taylor's capabilities emphasize job shop production.
3. Poly-Trussions and Fibco are limited respectively to pultrusion or vacuum bag and compression molding.

RECOMMENDATION:

1. Prepare an SOW defining subcontractor support requirements for follow-on composite effort.
2. Coordinate SOW with candidate subcontractors and obtain quotations for inclusion in follow-on proposal to be prepared in Task V (7/15-9/15).

TABLE I

SUMMARY OF SUBCONTRACTOR POSITIONS
REGARDING PRODUCIBILITY AND DESIGN*

ROCKET ENGINE PART	REYNOLDS & TAYLOR	SWEDLOW	FIBCO	M.C. GILL	POLY-TRUSSIONS	HITCO
1196001 LCH ₄ High Speed TPA	1B, 1C, 1E, 3A, 3B, 3C, 3F, ₄	1B, 1C, 1D, 3A, 3B, 3F, ₄	2A	1B, 1C, 1E, 3A, 3B, 3E, 3F, ₄	2A	1B, 1C, 1E, 3A, 3B, 3F, ₄
1196002 High Speed LOX TPA	1B, 1C, 1E, 3A, 3B, 3C, 3F, ₄	1B, 1C, 1D, 3A, 3B, 3F, ₄	2A	1B, 1C, 1E, 3A, 3B, 3E, 3F, ₄	2A	1B, 1C, 1E, 3A, 3B, 3F, ₄
1196003 LOX Low Speed TPA	1A, 1B, 1E, 3A, 3B, 3C, 3F, ₄	1A, 1B, 1D, 3A, 3B, 3F, ₄	2A	1A, 1B, 1E, 3A, 3B, 3E, 3F, ₄	2A	1A, 1B, 1E, 3A, 3B, 3F, ₄
1196004 Support Structure Throat Combustion Chamber	1B, 3B, 3F, ₄	1B, 3B, 3F, ₄	1B, 3B, 3F, ₄	1B, 3B, 3F, ₄	2A	1B, 3B, 3F, ₄
1196005 Seat-Gimbal Bearing	1A, 1E, 3A, 3B, 3C, 3F, 3G, ₄	1A, 1D, 3A, 3B, 3F, 3G, ₄	2A	1A, 1E, 3A, 3B, 3F, ₄	2A	1A, 1E, 3A, 3B, 3F, 3G, ₄
1196006 Shaft-Nozzle Extension	1B, 3B, 3F, 3G, ₄	1B, 3B, 3F, 3G, ₄	1B, 3B, 3F, 3G, ₄	1B, 3B, 3E, 3F, 3G, ₄	2B, 3D, ₄	1B, 3B, 3F, 3G, ₄
1196007 Injector Housing	1B, 1C, 1E, 3A, 3B, 3C, 3F, ₄	1A, 1B, 1D, 3A, 3B, 3F, ₄	2A	1B, 1C, 1E, 3A, 3B, 3F, ₄	2A	1B, 1C, 1E, 3A, 3B, 3F, ₄

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* See Notes on next page for legend explanation.

TABLE I (cont'd)

NOTES

1 PRODUCIBLE

- A. Extensive part-geometry redesign is required. Consideration should be given to structural requirements because of their effect on fiber geometry and fiber misalignment tolerances. Extensive use of chopped molding compound (isotropic material) in low stress areas would promote the producibility of thick sections and complex surfaces where it is difficult to maintain precision fiber alignment.
- B. A series of concurrent and congruent processing and fabrication steps are required.
- C. Minor part-geometry redesign would simplify fabrication.
- D. Subcontractor would prefer to assume basic design responsibility for the part.
- E. Subcontractor would prefer to act as a design consultant to guide producibility.

2 OUT OF MANUFACTURING SCOPE

- A. Lack processing facilities.
- B. Fabrication with graphite fiber must be segregated to prevent electrical equipment malfunctions.

3 PROCESSES

- A. Compression molding
- B. Autoclave molding
- C. Transfer molding
- D. Pultrusion
- E. Braiding
- F. Hand lay-up
- G. Wrapping, winding

- 4 Subcontractor would like to submit a quote to be included in the Composite Material Applications Study Contract Final Report.

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COMPANIES AND PERSONS CONTACTED

<u>COMPANY</u>	<u>PERSONS CONTACTED</u>	<u>PRODUCTS</u>
Reynolds and Taylor 2109 South Wright Street Santa Ana, CA (714) 540-4850	Mike Furry Vice President-Fabrication	Wings of composite material for the Israel smart bomb - Transfer molded stringers and integral fiberglass stress skins.
Swedlow, Inc. 12122 Western Avenue Garden Grove, CA (714) 893-7531	George Greenwald Manager Design Joe Kertesz Production Engineering Supervisor Glenn Cook Project Engineer Earl Gruhn Tony Chevalier Production Engineers John Progue Contract Administrator	Aircraft canopies, structural shapes, microwave antenna
Fibco Plastics, Inc. 6899 Oran Circle Buena Park, CA (714) 522-1161	Tony Rivera	Radomes, microwave antenna

PRODUCTS

E-9

Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

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Company: Reynolds and Taylor

Location: 2109 SOUTH WRIGHT ST
Santa Ana, Ca.

Telephone: 714-540-4850

persons contacted: ^{Mr. C. A. Smith} ~~Mr. C. A. Smith~~ in President's fabrication,
Don Harrison, Sales

business scope: Subcontractor of Kierford
Plastic parts to the Aerospace Industry

processes used: Autoclave, Vacuum bag, Compression
Resin injection, molding

related experience: Production contracts with Hughes
Aircraft, Lockheed, Litton, TRW Space Systems, Aerojet.
They ^{also} make parts for engineering studies. Much of
their work is with advanced composites.
Interested in Aerojet/NASA contract: yes

Remarks: Three divisions: Machinery, Composites,
Materials. They requested a visit to
observe their facilities. Sending a brochure
describing the company.

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Interim Survey Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

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Company: Peterson Products

Location: 1325 Old Country Rd
Belmont, Ca

Telephone: (415) 591-7311

persons contacted: Ken Anderson, manager

business scope: Job shop supplier of reinforced plastic parts to the building, electronics, and aerospace industries

processes used: Vacuum, compression molding, and resin transfer molding (reaction injection molding).

related experience: P.T. type development contracts with Lockheed, Ford Aerospace, -B11. R. in US Navy contractor a few years ago.

Interest in Aergit/NASA contract: yes

Remarks: Sending a Boelter Photo Letter

Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

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Company: Poly-Truccions Inc.

Location: 3050 Daimler St.
Santa Ana

Telephone: (714) 557-5802

persons contacted: Dell Miller, Engineer

business scope: Manufacturing of commercial fiberglass putrussions.

processes used: Putrusion and minor amounts of compression molding.

related experience: No. Similar. They appear to have considerable experience in putrusion and knowledge of how to produce graphite and Kevlar.

Interest in Aerojet/NASA contract: Yes, Poly-Truccions would like to help us develop the nozzle deployment system simulator aids. They

Remarks: Take with 100% in their integrity. fiberglass mat surface into which carbon fibers would be ground. This approach has been used in the past to make start thrust in simulator systems.

Dell estimates that between 5 and 10 thousand dollars of tooling would be required and perhaps a week of machine tools to optimize the port. Dell is sending a company brochure.

Dell suggested Reynolds and Reynolds as a plastic fabricator of aerospace parts.

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Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

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Company: Swedlow Inc.

Location: 12122 Western Ave
Garden Grove, Ca

Telephone: (714) 893-7531

1-76 Will return call

Persons contacted: John Pogue ^{Contract Adm.} & Joe Sullivan ^{Marketing}
Bill Yamaguchi

Business scope: Contract supplier of assorted reinforced plastic parts for government and commercial products.

Processes used: Hand lay-up, vacuum, autoclave, hydroclave, compression molding
(max capacity: 2000 ton, 56x60 in)

related experience: Many contracts with Aerojet Strategic and Lockheed Companies supplying ballistic missile components. They have done design and prototype contracts to the Navy.

Interest in Aerojet/NASA contract: Yes, would be interested in helping us develop advanced composite rocket engine parts. Sending a brochure and Engineering data book.

Remarks:

Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

Company: HITCO

Location: 1600 W. 135th Street
Gardena, Ca

Telephone: (213) 321-8080

persons contacted: Bill Curran, Contract Administrator
Don Owen, Pat Dempsey

business scope: Fabricator of High Temp.
AEROSPACE Structures

processes used: Autoclave, Hydroclave,
Compression Molding

related experience:

Interest in Aerojet/NASA contract: yes

Remarks:

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Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

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Company: Century Plastics, Inc

Location: 1435 S. Santa Fe
Compton Ca.

Telephone: (213) 637-1121

Persons contacted: Mr. Green, Principal and General Manager

Business scope: Job shop fabricator of reinforced plastic parts, primarily for electrical applications.

Processes used: Vacuum Bag Molding, Autoclave molding, Compression Molding (1500 Ton capacity)

related experience: Autoclave molded a prototype spider part of Kevlar epoxy for the L-1011. Developed a graphite stiffener part for FMC.

Interest in Aerojet/NASA contract: Yes.

Remarks: Employ a retired Lockheed Engineer as a consultant three days a week. The consultant is an instructor at the Howey Mudd Institute. He would like the consultant to be present when we visit their facility to discuss our requirements.

6-9-82

Preliminary Subcontractor Survey

① Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

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Company: Fibco Plastics Inc.

Location: 6899 Oren Circle
Buena Park, Ca

Telephone: (714) 522-1161

Persons contacted: ^{Tom} Tom Rivera: Father owns company. Father started company 22 years ago and has the primary technical expertise

② Business scope: Job shop fabricator of small production runs and prototype parts.

Processes used: Hand lay-up, Vacuum and autoclave molding, and compression molding

Related experience: Have made parts for Aerojet in Buena Vista and El Monte. Have frequently quoted work from Asuzga. Manufacture radomes for EA-6 and P-3 aircraft, NASA, and the Navy. They supply the 11 foot radome covers for the Navy Terrier missile system.
Interest in Aerojet/NASA contract: yes.

③ Remarks: We should discuss our technical requirements with Tom's father. They are sending us some literature describing the technical capabilities of the company.

Preliminary Subcontractor Survey

Purpose: To identify subcontractors to be evaluated as potential suppliers of rocket engine parts made of composite materials.

Company: M.C. Gill Corp.

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Location: 4056 Easy Street
El Monte, Ca

Telephone: (213) 443-6094

persons contacted: Dennis Watts, manager of commercial aircraft division, Steven Gill, manager of the Hitehite operations.

business scope: Job shop manufacturer of reinforced plastic parts for the commercial aircraft industry.

processes used: Vacuum, autoclave, and compression molding.

related experience: They have conducted manufacturing development programs involving graphite epoxy and Kevlar epoxy. McDonald Douglas and the Dahlgren labs of the US Navy.

Interest in Aerojet/NASA contract: They have studied polyimide resin and have quoted several jobs for McDonald Douglas. They are especially interested in pursuing a development program using polyimide resins.

Remarks: They have a process development lab in El Monte and we would be welcome to participate in any experiments conducted for us.



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Materials Analysis

REPORT NO. MA-82-156

DATE 21 September 1982

WORK REQUESTED BY

D. C. Judd

DEPT:

9772

PAGE 1 OF

4

SUBJECT

Application of Metal Matrix Composites
to Selected Engine Parts

TABLES:

FIGURES:

PROGRAM

Composite Materials Application
to Liquid Rocket Engines

W.O. NO.

2418-05-000

ENCLOSURES:

PART NAME

PART NO.

S/N

MATERIAL

PURPOSE:

To consult with metal matrix composite fabricators to determine the
state-of-the-art for application to selected liquid rocket engine parts.

DISTRIBUTION

EW Carter
D Culver
DL Kors
R Michel
RO Schwantes

REPORT BY

G. R. Janzer

REVIEWED BY

APPROVED BY

VEITCH, MANAGER MATERIALS ANALYSIS SECTION

DISCUSSION:

The writer and Ed Carter visited Nevada Engineering and Technology Corp. (NETCO) of Long Beach, California, and DWA Composite Specialties, Inc. of Chatsworth, California, on 10 September, for consultation with regard to the application of metal matrix composites to the subject program.

NETCO

The NETCO contacts were Leroy Davis, President, and Jack Williamson. The purpose of visiting NETCO was twofold. In addition to the aforementioned consultation, NETCO is expected to be a source for mechanical and physical property data for proposed designs. NETCO is under contract to the Department of Defense Metal Matrix Composites Information Analyses Center (MMCIAC) to collect, evaluate, store and disseminate metal-matrix property and processing data. Mr. Davis was asked to provide MMCIAC cryogenic property data for support for the design activity of the anticipated composites follow-on contract. He stated that there was very little cryogenic information; and since this activity is just getting underway, the material is not fully organized for immediate retrieval. Mr. Davis is placing the writer on distribution for the MMCIAC bulletin and will determine the availability of cryogenic data at a later date.

When the drawings were presented, Messrs. Davis and Williamson stated that they preferred not to comment on the viability of the design from the standpoint of fabrication from metal matrix composites due to their complexity as compared to their experience. They recommended consulting with either AVCO, DWA or MCI for fabricability information. They believed that DWA would be the best source for this information and did offer an opinion that fabrication would be very difficult.

Mr. Williamson wanted to comment on the design with regard to reinforced plastic (RPC) materials since he is also marketing director for Reynolds and Taylor, a company which had declined to respond to an RFQ from ALRC on the subject RPC designs. He said he would persuade his associates at Reynolds and Taylor to reconsider their no-bid position.

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Page 3

DWA

The DWA contacts were Joe Dolowy, President, Bill Harrigan, General Manager-Operations and Roy Levin, Manager-Manufacturing Development. After the writer and Ed Carter described the composites contract, Joe Dolowy stated they were already somewhat familiar with the program since they had consulted with Rocketdyne on their parallel effort. Their examination of the drawings resulted in a unanimous opinion that the parts could not be fabricated by laying-up metal matrix laminates and diffusion bonding. They said that not only could the parts not be layed up due to the small and varying radii, but that hot gas isostatic pressing (HIP) for diffusion bonding would be a development program in itself. They specifically stated that the most complex part, the pump housing, was well beyond the present state of metal matrix composite fabrication capability. It was also their opinion that for complex shapes with multi-directional stress distributions, boron-aluminum becomes inefficient and that graphite-metal composites present the same problem in addition to the problem of very low transverse and shear strength. They proposed fabricating from their proprietary aluminum-silicon carbide reinforced composite material, DWA-Al. This material is a powder metallurgy product, which is consolidated into semi-finished stock prior to being processed by conventional metal shaping techniques such as forming, extrusion, forging and machining. The material possesses poor weldability by the GTAW process and is considered by DWA to be unweldable by the electron beam process. Weld deposits are porous and have the same properties as those deposited on unreinforced aluminum alloys. DWA stated that they have made good progress in reducing weld porosity, and presented photomicrographs showing porosity limited to the weld deposit heat affected zone interface. They expect to further improve weld soundness and are currently developing composite weld rods for producing reinforced, higher strength weld deposits. This development has led to their initiating a casting program. DWA could not provide assurance that these technologies would be sufficiently developed for application for our follow-on contract.

The writer inquired whether the aluminum graphite composite, which can be tailored to match the expansion coefficient of the RFP material, could be applied as liners for the interior of RFP parts. Their response was negative.

Mr. Dolowy said that DWA would provide a written cost estimate for the one part, the valve body. He would propose to machine the part from an extrusion and gave a preliminary estimate of \$50,000.

CONCLUSIONS AND RECOMMENDATIONS:

1. Fabrication of the candidate parts by diffusion bonding of metal matrix composite laminates would be very difficult and is considered a high risk item.

2. A material such as the DWA-A1 composite offers the lowest risk in the application of metal matrix materials to the unwelded, candidate parts. Welded designs must account for reduced strength and some weld porosity.

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composite specialties, inc.

16 September 1982

Aerojet Liquid Rocket Company
P.O. Box 13222
Sacramento, CA 95813

Attention: Messrs. Ed Carter and George Janser

Subject: Meeting at DWA 10 September 1982

Gentlemen:

With regard to your visit of last week, we have reviewed the structures discussed and have reached similar conclusions to those reached during the meeting. Of the five structures considered: 1) the LCH₄ High-speed TPA appears to be well beyond the present state of MMC fabrication capability; when truly "castable" forms of discontinuous composites become available, large toroidal or volute type structures will become do-able. 2) & 3) The Support ring and nozzle extending shafts were only considered in passing, since they didn't offer any appreciable weight saving or technology challenge; both could be impacted with metal matrix. 4) Injector Housing represents a significant challenge to present discontinuous reinforced MMC fabrication technology. Utilizing forged DWAL 20[®] for the bottom third and top third of the part while handling the oxidizer manifold as a separate problem seems most efficient (fabricate as a separate "pressure-vessel" type structure, utilizing conventional material, or possibly superplastically formed DWAL 20[®]). Forged "cup"[®] "complex-base" cylinder shapes have been produced with DWAL 20[®]. The most significant problem with the injector housing would evolve from assembling the three subcomponents; brazing and welding both seem reasonable, but a development program would be advised. If necessary, selective circumferential reinforcing could be applied, using graphite epoxy; this could also aid in assembling the subcomponents. 5) Housing-valve, propellant - represents the second structure discussed 10 September, with reasonable options for MMC demonstration. Extruded, heavy-wall cylinders represent a straightforward approach, but necessitates significant machining to create bosses, attach-points and flanges. An alternative fabrication process could utilize ring-rolling to decrease the required machining, but this would necessitate higher tooling costs.

In reviewing the Aerojet selected hardware, my associates and I felt the DWAL 20[®] (isotropic particulate-reinforced P.M. composite) would be most appropriate. Although our experience with boron-aluminum-type composites exceeds all other material systems when axi-symmetric, rather complex-shaped parts (with multi-directional stress distributions) are desired, B-Al tends to

E-23

21133 superior street, chatsworth, ca. 91311 (213) 998-1504

9/16/82

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become inefficient. Also, the complexities of fabrication with continuous, stiff fibers limit available processes. The graphite-metal composites were not considered for similar reasons, with the added problem of very-low transverse and shear strength. The ability to utilize many conventional metal-working processes and to yield isotropic mechanical properties, has finalized the recommendation of DWA 20 materials.

In response to questions generated during the meeting, attached are several tables showing mechanical properties and costs of various MMC systems. A generalized development effort for the valve housing might require five or six months, with initial extrusion experiments yielding 8-inch long x 2.2" ID x 4.8" OD samples. Subsequent machining would create the final product. A \$35K to \$45K effort should be sufficient.

The injector housing structure, which would involve a much greater analysis effort, separate tools, and an assembly task would necessitate a ten to twelve-month effort. Initially, the design concept and part sizes would be finalized with the selection of material for the oxidizer manifold. Forging, or hot-forming tools for the top and bottom sections will be produced; then axisymmetric tool-verification parts generated. Mechanical property levels verified from the "tool try" parts following NDT, would create mechanical-property data. The assembly technique would be demonstrated (braze, or weld with option of Cr-Epoxy overwrap, or adhesive bond) with a final assembly, proof test, and inspection sequence. This program would require support to about \$100K.

I hope your MMC study program with NASA is a success. We at DWA would be happy to support Aerojet Liquid Rocket in any design, trade-off, or prototype hardware efforts using any metal-matrix composite materials. We look forward to your comments on this letter.

Very truly yours,

DWA COMPOSITE SPECIALTIES, INC.


J.F. Dolow, Jr.
PresidentJFD:ls
80611

cc: T.D. Lynch

APPENDIX F
TECHNOLOGY NEEDS DEFINITION FORMS

TECHNOLOGY NEED DEFINITION

ITEM:

1.0 - H₂ Compatibility

DESCRIPTION:

Select composite materials that are not degraded by exposure to hydrogen.

ASSESSMENT OF RISK:

High *

Medium

Low

- * Freeze-thaw cycling of hydrogen rocket propellant (and other vapors) trapped in composite material has the potential to cause severe structural damage. The glass transition temperature of epoxy resin used in high performance structural composites have glass transition temperatures above ambient. At use temperatures below the glass transition, mechanical properties show improvement. Also at cryogenic temperatures, hydrogen is chemically unreactive and not a cause of resin degradation.

APPROACH:

The effects of mechanical property degradation resulting from freeze-thaw cycling can be demonstrated. The rate of degradation should depend upon the permeability of the composite. It is believed impractical to control mechanical property degradation by resin selection.

PROPOSED SOLUTION:

Barrier coatings, liners, etc.

TECHNOLOGY NEED DEFINITION

ITEM:

2.0 - O₂ Compatibility

DESCRIPTION:

Select composite materials that are not degraded by exposure to LOX.

ASSESSMENT OF RISK:

High *

Medium

Low

- *1. If freeze-thaw (also condensation) cycling occurs.
- 2. Most organic polymers used as matrices in high performance composite materials are expected to fail LOX impact requirements (MSFC-SPEC 106).

APPROACH:

Poly (amide-imide) resin matrix may pass LOX impact requirements. It is believed impractical to control degradation caused by freeze-thaw cycling through material selection.

PROPOSED SOLUTION:

Barrier coatings, liners, etc.

TECHNOLOGY NEED DEFINITION

ITEM:

3.0 - CH₄ Compatibility

DESCRIPTION:

Select composite materials that are not degraded by exposure to methane.

ASSESSMENT OF RISK:

High *

Medium

Low **

- * If freeze-thaw (also condensation) cycling occurs.
- ** 1. Temperature too low for chemical degradation.
- 2. Methane absorption will not make worse the effects of any polymer transitions occurring because of low temperature.

APPROACH:

It is believed impractical to control degradation of mechanical properties due to freeze-thaw cycling through material selection.

PROPOSED SOLUTION:

Barrier coatings, liners, etc.

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TECHNOLOGY NEED DEFINITION

ITEM:

4.0 - Low Temperature Toughness

DESCRIPTION:

Select composite materials that are thermal shock and impact resistant.

ASSESSMENT OF RISK:

High

Medium

Low *

* Composite materials have inherent toughness properties because of their energy absorbing fracture characteristics. These characteristics increase slightly at cryogenic temperatures to improve toughness performance.

APPROACH:

Fiberglass reinforcement and graphite fiber reinforcement are used successfully in cryogenic structural applications. Fiberglass is preferred for applications requiring thermal insulation. Graphite is preferred for applications requiring higher thermal conductivity or greater stiffness.

PROPOSED SOLUTION:

Select composite materials on the basis of room temperature structural properties and validate their structural performance at cryogenic temperatures by conducting structural element tests.

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TECHNOLOGY NEED DEFINITION

ITEM:

5.1 - Mechanical Fastening

DESCRIPTION:

Bonded metallic inserts for composite materials may pull out because of thermal contraction at cryogenic temperatures.

ASSESSMENT OF RISK:

High

Medium

Low *

- * Mechanically anchored inserts are available that do not pull out easier because of shrinkage.

APPROACH:

Review applications of mechanical fasteners to make sure that bonded inserts are not used where insert shrinkage would result in an attachment failure.

PROPOSED SOLUTION:

Avoid using bonded metallic inserts in composites at cryogenic temperatures.

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TECHNOLOGY NEED DEFINITION

ITEM:

5.2 - Finish of Fluid Sealing Surfaces

DESCRIPTION:

Smooth surfaces are required for O-rings and seals. Machining high performance composite materials may not meet the finish requirements for seals.

ASSESSMENT OF RISK:

High

Medium

Low *

- * Coatings can be used to improve the finish of machined composite materials.

APPROACH:

Select coating compounds for use with lubrication seals.

PROPOSED SOLUTION:

Coatings to upgrade the finish of machined composite surfaces will be used.

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TECHNOLOGY NEED DEFINITION

ITEM:

5.3 - Vane Manufacturing Method

DESCRIPTION:

Select a manufacturing process to mold the TPA stator vanes.

ASSESSMENT OF RISK:

High

Medium

Low *

* Alternate methods for molding the stator vanes are available.

APPROACH:

Allow the manufacturer of the TPA housing to determine the best manufacturing method for this part.

PROPOSED SOLUTION:

The stator vanes may be molded in-place (in situ) or molded separately and bonded in place.

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TECHNOLOGY NEED DEFINITION

ITEM:

5.4 - Vane Attachment Method

DESCRIPTION:

An adhesive bonding process must be developed if the manufacturer elects to mold these details separately.

ASSESSMENT OF RISK:

High

Medium

Low *

- * Adhesives for bonding composite materials at cryogenic temperatures are available.

APPROACH:

The manufacturer of the TPA assembly will select an adhesive and bonding process that will satisfy the structural requirements of the design disclosure.

PROPOSED SOLUTION:

The shear stress between the stator vanes and the turbine manifold shell may exceed the interlaminar shear capability of the composite. In this case more composite material will be required to reduce this stress.

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TECHNOLOGY NEED DEFINITION

ITEM:

5.5 - Residual Thermal Stresses

DESCRIPTION:

Determine the effect that the cure cycle has on the residual stress of each design.

ASSESSMENT OF RISK:

High

Medium *

Low

- * Distortion and ply failure due to thermal stress at cryogenic temperatures can be avoided by controlling the fiber orientation.

APPROACH:

Analyze the effects that the fabrication process has on residual stress. Design the process and laminate to minimize thermal distortion and failure.

PROPOSED SOLUTION:

Control residual thermal stress through design analysis and process control.

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TECHNOLOGY NEED DEFINITION

ITEM:

5.6 - Barrier Coating Process

DESCRIPTION:

High performance plastic composites must be sealed in order to contain liquids and vapors.

ASSESSMENT OF RISK:

High *

Medium

Low

- * Microcracking occurs in the resin matrix of high performance composite materials. These cracks result from residual and applied stresses. They render the resin matrix permeable to vapors and liquids.

APPROACH:

Several barrier coatings (metal foils, plastic films, etc.) have been used successfully to seal composite materials. These coating materials and processes will be evaluated to select the optimum system for a given rocket engine component.

PROPOSED SOLUTION:

Ductile barrier coatings are required to seal composite materials.

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TECHNOLOGY NEED DEFINITION

ITEM:

5.7 - Plumbing Connections

DESCRIPTION:

Propellant line connections are a primary source of propellant leaks. Composite materials are expected to cause more leak problems than metals because they scratch and distort more readily.

ASSESSMENT OF RISK:

High

Medium

Low *

- * Viton, Kryton, Teflon, Kel-F, and metal foils are materials available to seal propellant line connections.

APPROACH:

Evaluate seals and O-rings to determine the most effective method to produce leak-resistant plumbing connections.

PROPOSED SOLUTION:

More extensive use of metals in flanges will be necessary if leak-resistant connections using composites fail.

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ITEM:

5.8 - Adhesive Bonding

DESCRIPTION:

Adhesives and adhesive preregs which join composite materials in liquid rocket engine applications must satisfy the same compatibility requirements as the composite.

ASSESSMENT OF RISK:

High *

Medium

Low

- * Melt processible PCTFE and poly (amide-imide) might provide propellant compatible adhesive systems (TBD). Otherwise barrier coatings will be required.

APPROACH:

Freeze-thaw cycling damage is not as serious a problem for adhesive bonding applications because resin microcracking does not occur. Propellant exposure tests may indicate that a protective barrier will only be required for LOX.

PROPOSED SOLUTION:

Barrier coating, liner, etc.

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ITEM:

5.9 - Fabrication Methods

DESCRIPTION:

Alternative methods are available to mold composite materials (compression, autoclave, resin injection, etc.).

ASSESSMENT OF RISK:

High

Medium

Low *

- * An analysis of the structural effects of alternative processes may indicate a change in the structural capability of the part.

APPROACH:

The effects of processing must be validated in structural tests. A trade-off between structural performance and producibility will be made.

PROPOSED SOLUTION:

Revised design allowables will be issued if the choice of a process affects the structural properties of the material.

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ITEM:

5.10 - Mold Design

DESCRIPTION:

A mold to produce composite parts should be capable of meeting all the design objectives specified for the part.

ASSESSMENT OF RISK:

High

Medium *

Low

- * Analysis of the mold performance before building the mold will reduce costly iterations in process and mold design to solve problems involving producibility.

APPROACH:

An analysis of the mold performance should be made to determine if any design changes are needed. The analysis should investigate the effects of compaction, flow, temperature rise, cure uniformity, cool down, and concentration of reinforcement and resin on residual thermal stress, shrinkage, and voids.

PROPOSED SOLUTION:

Redesign the mold until analysis indicates that the part is satisfactory or lower the part specification to reflect what is possible before releasing the mold design for fabrication.

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ITEM:

6.0 - Cryogenic Properties

DESCRIPTION:

Some commercial composite materials have useful structural properties at cryogenic temperatures. Their outstanding fracture toughness is due to microcracking of the resin matrix to relieve residual thermal strain.

ASSESSMENT OF RISK:

High

Medium

Low *

- * Commercial composite materials have met the requirements of application at cryogenic temperature because of good fracture toughness and moderate increases in mechanical properties.

APPROACH:

Candidate composite materials will be tested at cryogenic temperatures to determine their structural properties. Structural tests following cryogenic temperature cycling will also be conducted to evaluate the stability of the fiber matrix bond.

PROPOSED SOLUTION:

Commercial composites will not be applied beyond their temperature limits. Efforts will be made to obtain composite materials having improved fracture toughness properties at cryogenic temperatures.

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ITEM:

7.0 - Interface Properties

DESCRIPTION:

Many kinds of interfaces occur in composite materials. Interfacial instability may occur because of corrosion, stress, debonding, etc.

ASSESSMENT OF RISK:

High *

Medium

Low

- * The low temperature stability of adhesive interfaces because of thermal stress is a familiar problem, especially acute for metallic interfaces.

APPROACH:

Tests will characterize the stability of composite material interfaces in liquid rocket engine applications. These tests will determine which kinds are acceptable in design and which are not.

PROPOSED SOLUTION:

Unstable interfaces can not be used because of the potential for progressive structural failure. Metallic parts would replace composite parts in any applications involving unstable interfaces.

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ITEM:

8.0 - Metal Coating Interface Properties

DESCRIPTION:

Cycling temperature and pressure can fail the metallic barrier coating protecting the composite. Two techniques may impart more durability to the protective barrier: (1) Metallized plastic film, (2) Elastomeric adhesive.

ASSESSMENT OF RISK:

High

Medium

*

Low

- * Elastomeric adhesives have demonstrated low temperature bonding capability to metal and metallized plastic film. Their performance at cryogenic temperatures needs to be determined (TBD).
TBD

APPROACH:

Evaluate the bond stability by cycling the test specimens between ambient and cryogenic temperature. Specimens consist of (1) metal bonded to composite with an elastomeric adhesive and (2) metallized film bonded to composite with an elastomeric adhesive. Failure of the elastomeric adhesive bond will result in a more sophisticated approach to stabilize the bond. A tie coat adhesive, approximating the thermal expansion of the metal, will be evaluated with the elastomeric adhesive.

PROPOSED SOLUTION:

Composite materials can not be used in applications requiring protective coatings if the tests above and the supporting analysis indicate that the barrier coatings fail to meet the strain cycling requirements.

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ITEM:

9.0 - Differential Expansion Properties

DESCRIPTION:

The thermal expansion properties must be known in order to analyze the thermal stresses affecting design.

ASSESSMENT OF RISK:

High

Medium

Low *

- * The anisotropic thermal expansion coefficients (α_x and α_y) can be used to calculate residual thermal stress.

APPROACH:

Thermal expansion data will be obtained from the material suppliers or from ALRC lab tests.

PROPOSED SOLUTION:

Without this data the analysis of thermal effects to support design will be less accurate.

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ITEM:

10.0 - Solar Radiation Effects

DESCRIPTION:

Protective coatings are needed to protect the surface of plastic matrix composites from polymer degradation.

ASSESSMENT OF RISK:

High

Medium

Low *

- * The absorption of radiation by the reinforcement limits damage to the surface. In most applications the most serious effect is cosmetic.

APPROACH:

Select protective coatings that are compatible with the rocket engine environment for use on surfaces exposed to solar radiation.

PROPOSED SOLUTION:

If coatings are not used to protect against radiation, small losses in strength will occur due to surface degradation.

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ITEM:

11.0 - Low Cycle (Thermal) Fatigue

DESCRIPTION:

Cycling temperatures can result in structural failure.

ASSESSMENT OF RISK:

High

Medium *

Low

- * Distortion and ply failure due to thermal stress can be avoided by controlling the reinforcement orientation.

APPROACH:

Conduct a thermal-stress analysis to identify any structural elements that exceed allowable ply stresses.

PROPOSED SOLUTION:

Without this analysis the chances of LCF failures increase.

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ITEM:

13.0 - Bearing Surface Lubricant

DESCRIPTION:

A lubricant applied to the nozzle extension shaft threads will reduce friction, stress, and wear.

ASSESSMENT OF RISK:

High

Medium

Low *

- * Surfaces of plastic composite materials erode faster than metal surfaces for a variety of reasons. Lubricants will reduce friction and wear.

APPROACH:

Select a commercial lubrication system compatible with composite materials, the liquid rocket engine environment, and the vacuum conditions of space.

PROPOSED SOLUTION:

Without a lubrication system, the useful life of the shaft will be shortened due to excessive wear.